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FINAL REPORT

Contract Number FA—WA—4632

Project Number 221-140-02C (423-1)

WIRELESS CONTROL SYSTEM FOR AIRPORT LIGHTING

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FEDERAL AVIATION AGENCY

Systems Research & Development Service

by

BERNARD ELECTRONICS COMPANY

Washington, D. C.

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WIRELESS CONTROL SYSTEM FOR AIRPORT LIGHTING

January 1965

Prepared By
Arthur H. Ballard

This report has been prepared by Bernard Electronics Company for the Systems Research and Development Service, Federal Aviation Agency, under Contract No. FA-WA-4632. The contents of this report reflect the views of the contractor who is responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policy of the FAA. This report does not constitute a standard specification or regulation.

BERNARD ELECTRONICS COMPANY
WASHINGTON, D. C.

ABSTRACT

An experimental system for wireless control and monitoring of airport lighting was developed with the objective of providing a cheaper more flexible and reliable system than existing cable systems.

The system provides 16 channel capacity on a single FM carrier with a maximum range of 3 miles. Three channels (selectable) provide on-off, 5-step of continuous control in the form of 0-10 volt dc commands. Remote stations reply automatically with identical signals to actuate displays at the master station. Electrical comparison of signals indicate incorrect reply or failure in any channel. Failsafe provisions at each remote station switch the lighting equipment to full on, full off, or the last commanded brightness in the event of system failure.

High spectrum efficiency, and maximum rejection of noise, cross-talk, and interference is achieved through the use of a previously developed multiplex technique. Orthogonal pulse waveforms are employed as subcarrier signals, which are generated digitally and amplitude-modulated by diode multipliers. Channel separation and demodulation is accomplished by correlation with locally-generated subcarrier waveforms. All remote stations are automatically synchronized to a timing reference subcarrier by similar correlation techniques.

When engineered for quantity production, system cost is estimated to be approximately $2,000 per 2-way channel, including RF equipment.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

The purpose of work on this contract was to develop a multi-channel wireless control system suitable for remote actuation, control and monitoring of airport lighting installations, which would be cheaper and more flexible than existing buried cable systems.

The airport lighting installations to be controlled are those which serve as visual aids to aircraft landing, surface movement, and take-off operations. To meet changing conditions of weather and traffic, these lights must be selectively controlled in brightness by airport tower personnel. A need exists not only for on-off control but also for 5-step control or continuous (stepless) control of brightness.

The lighting installations to be controlled are usually remote from the control tower itself - at distances as great as 3 miles for the larger airports. Selective control of these installations which are widely dispersed over the airport surface requires a complex distribution system for command data. The problem is further complicated by the fact that the lights are often directed away from the tower and are not directly visible to control personnel. A need also exists, therefore, to send back monitoring data over the same distribution system to assure control personnel that command signals have actually produced the proper response.

Until the present time, control signals for airport lighting have been carried over buried cable systems, which are relatively expensive and inflexible. Minimum cost of opening and closing a cable trench is about $1.00 per foot, so that a 3-mile installation might cost as much as $15,000. If the trench must cross an existing apron or runway, the cost could easily be higher. Furthermore, expansion or modification of the airport surface layout frequently entails cable relocation costs comparable to the initial installation cost.

By way of contrast, a wireless control system can be provided at an initial cost of something like $2,000 per 2-way channel, including r-f equipment. Negligible expense is involved in relocation of the terminal stations. Wireless control systems do present the following problems in applications of this type.

(1) The radio spectrum available for airport surface use is extremely limited, and the necessary control and monitoring signals must be fitted into a minimum bandwidth r-f channel.

(2) The wireless control system must not interfere with the multitude of active radio channels existing at airports, nor must it be susceptible to interference by the existing radio spectrum environment.

On the present contract, most if not all of these objections have been met by means of a new multiplex modulation scheme. This previously developed technique makes use of orthogonal pulse waveforms as data sub-carriers for efficient multiplexing;and correlation detection for optimum rejection of crosstalk noise, and interference. By adapting this multiplex technique for two-way transmission on a single narrow-band F-M carrier, a very efficient, flexible, and reliable wireless control system has been obtained. The equipment required is sufficiently simple, that when engineered for quantity production, it should offer significant cost savings over buried cable systems.

SYSTEM REQUIREMENTS

The basic requirements for the Wireless Control System developed on this contract were set forth in the Statement of Work (Article I of Contract No. FA-WA-4632). These requirements were subsequently expanded and modified where necessary, as a result of conferences held between Bernard Electronics Company and technical representatives of the FAA. The system requirements ultimately agreed upon are summarized below.

(A) Operational Requirements

The Wireless Control System developed on this contract will permit a number of airport lighting installations to be controlled remotely from the airport control tower. The system design will permit as many as sixteen (16) remote stations to be controlled from a single master station; however, equipment for the control of any three (3) remote stations will be constructed for the experimental evaluation model.

Using two-way FM transmission on a single r-f frequency, the system will provide the following operational features for each lighting installation controlled.

1. Initiation at the master station and transmission to each remote station of brightness information in the form of continuously variable, 5-step variable, or on-off commands.

2. Repeat-back and display at the master station of brightness information as received (or operated upon) at each remote station.

3. Automatic alarm at the master station in the event that any remote station fails to reply, or replies incorrectly.

4. Automatic provision for causing the remote lighting installation to go to full on, full off, or the last commanded brightness in the event of system failure.

5. Provision for a standby mode of operation in which all equipments are turned on but none is transmitting on-the-air.

(B) Performance Specifications

Number of Control Channels:	Up to 16 (3 supplied initially)
Brightness Control Data:	
1. Continuously variable	0 to 10 volts d-c
2. 5-step variable + off	0, 2, 4, 6, 8, or 10 volts d-c
3. On-off	0 or 10 volts d-c
Repetion Rate of Commands:	16 cps
Duration of Commands:	1/80 sec, simultaneous for all remote stations
Query Signal (to initiate reply):	-10 volts d-c
Repetition Rate of Query/Reply	1 cps, each remote station
Duration of Query/Reply	1/80 sec, time-shared for all remote stations
Type of Emission:	16F9
R-F Frequency:	162.225 mc ± .0005%
R-F Bandwidth:	16 kc maximum
R-F Power:	10 watts maximum
Frequency Deviation	± 5 kc maximum
Subcarrier Signals:	Orthogonal Pulse Waveforms
Subcarrier Moduation:	Amplitude Modulation
Master Station Indicators (each channel):	
1. Command Data	Control Lever Setting
2. Reply Data	4-1/2" Vertical Edgewise Meter
3. System Failure	Red Indicator Lamp
4. Incorrect Reply	Yellow Indicator Lamp
5. Correct Reply	Green Indicator Lamp
Remote Station Output Signals	
1. Command Signal	0-10 volts d-c
2. Reference Signal	± 10 volts d-c
3. System Failure Signal	Release of relay contacts (1 Form C, 2 amp rating)
Primary Power:	
1. Master Station incl. control units	200 watts maximum
2. Remote Station, with heater	200 watts maximum
Operating Environment	
1. Control Units	For use in manned control tower
2. Master Station	-10°C to + 55°C, 0-95% humidity
3. Remote Station	-30°C to + 55°C, 0-95% humidity, wind, rain, sand, dust, salt spray

(B) Performance Specifications

Number of Control Channels:	Up to 16 (3 supplied initially)
Brightness Control Data:	
1. Continuously variable	0 to 10 volts d-c
2. 5-step variable + off	0, 2, 4, 6, 8, or 10 volts d-c
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Repetion Rate of Commands:	16 cps
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(C) Modifications To Original Requirements

The principal modifications to the original requirements, and the reasons for their adoption, were as follows:

(1) The system capacity was increased from 12 to 16 channels, since the latter design was found to be easily obtainable without incurring any penalty in other system parameters.

(2) In view of the many types of power-handling apparatus which might be connected to the remote station output signals, it was agreed to standardize input-output signals to the range 0-10 volts d-c with 5-step control corresponding to equal 20% increments of the full scale voltage. The design of interface equipment for adapting such signals to various power-handling devices was agreed to be outside the scope of the current contract.

(3) Since the master station equipment will be eventually integrated into existing FAA cabinet racks, it was decided that this equipment need not be supplied in a weatherproof case, and that operation only down to -10°C would be sufficient for the experimental model.

(4) A panel size of 6-3/4" by 4-1/4" for each control unit was deemed acceptable in the feasibility model, provided that the design did not prohibit future reduction to a 6" by 4" panel area.

(5) Successful operation of the remote station equipment at -10°C was considered sufficient to satisfy the low temperature requirement for the experimental model of this equipment provided that it be equipped with a heater to maintain a temperature of -10°C or higher inside the case.

(6) The system standby mode was included as a desirable feature to eliminate unnecessary r-f radiation when lighting control is not needed, yet avoiding excessive warmup time when control is needed.

(7) Failsafe protection was expanded to include an out-of-sync condition at any remote station, because such a failure might otherwise disturb the entire system.

PRINCIPLES OF DESIGN

(A) Input/Output Techniques

The types of lighting apparatus now in use at airports or under development are extremely varied. Some are merely on-off power relays while others provide 3 or 5 step control of brightness by tap-switching on a power transformer. Still others provide stepless control of brightness by means of a saturable reactor whose impedance is varied by a motor-driven variac. More recently, solid-state devices using silicon-controlled rectifiers (SCR's) have been developed for both step and stepless control.

In designing a wireless control system for use with any of these devices, the need for standardizing the form of input/output signals soon became apparent. It was also clearly desirable that the wireless control

system characteristics should remain independent of the calibration curve (brightness vs. control signal level) for any particular type of lamp or power control device.

For these reasons, it was decided to standardize all input/output signals to a single form. The form selected was 0 to +10 volts d-c, primarily because such signals can be processed readily with circuits using general purpose transistors. For stepless control, it was decided that the system should simply reproduce at each remote station, a linear variation of voltage between 0 and +10 volts d-c. On-off or 5-step control is obtained if the command mechanism at the master station is detented in equal 20% increments, corresponding to 0, 2, 4, 6, 8, or 10 volts d-c.

(1) Master Station

Figure 1 illustrates the input/output techniques adopted for the master station. Command signals are inserted by means of a thumbwheel is a pointer over-lying the scale of a vertically-mounted edgewise meter. The coupling is such that the pointer traverses the full range of the meter as the thumbwheel is moved from the first to the last detent position.

A two-section potentiometer is also coupled mechanically to the command thumbwheel to generate proportional electrical signals. The two sections are energized from fixed reference voltages of +10 volts and -10 volts respectively. Equal and opposite command voltage (a_n = 0 to +10 vdc, $-c_n$ = 0 to -10 vdc) are taken from the potentiometer arms, and applied to one set of channel input terminals of a multiplex transmitter. The use of equal and opposite data signals was adopted to simplify design of the balanced full-wave modulator circuits in the multiplex transmitter. The $\pm$10vdc reference voltages are common to all data channels and are transmitted to each remote station on a separate reference channel of the multiplex transmitter.

Each remote station will periodically send a reply signal to the master station indicating what command has been received or what action has occurred in response to that command. The reference signal as received at each remote station is also repeated back to the master station as a check on channel continuity.

Both the reply reference signal and the reply data signal for each channel are stored in output holding circuits to make them appear as continuous d-c voltages. Correct operation for a given channel is verified by comparing the reply reference signal, which should be a fixed -10 volts d-c, with the local +10 volts d-c reference supply at the master station. If they are not equal and opposite, a failsafe relay will release, causing the red alarm lamp for that channel to glow. If the reply reference voltage is approximately correct, the failsafe relay will energize, the red lamp will extinguish, and either the yellow or green lamp will glow.

The variable reply data signal (0 to +10 volts d-c) received for each channel is applied directly to the vertical edgewise meter for that channel. The command and reply signals for each channels can therefore be compared visually with maximum ease of interpretation. The command and reply signals are also compared electrically to determine if a discrepancy exists.

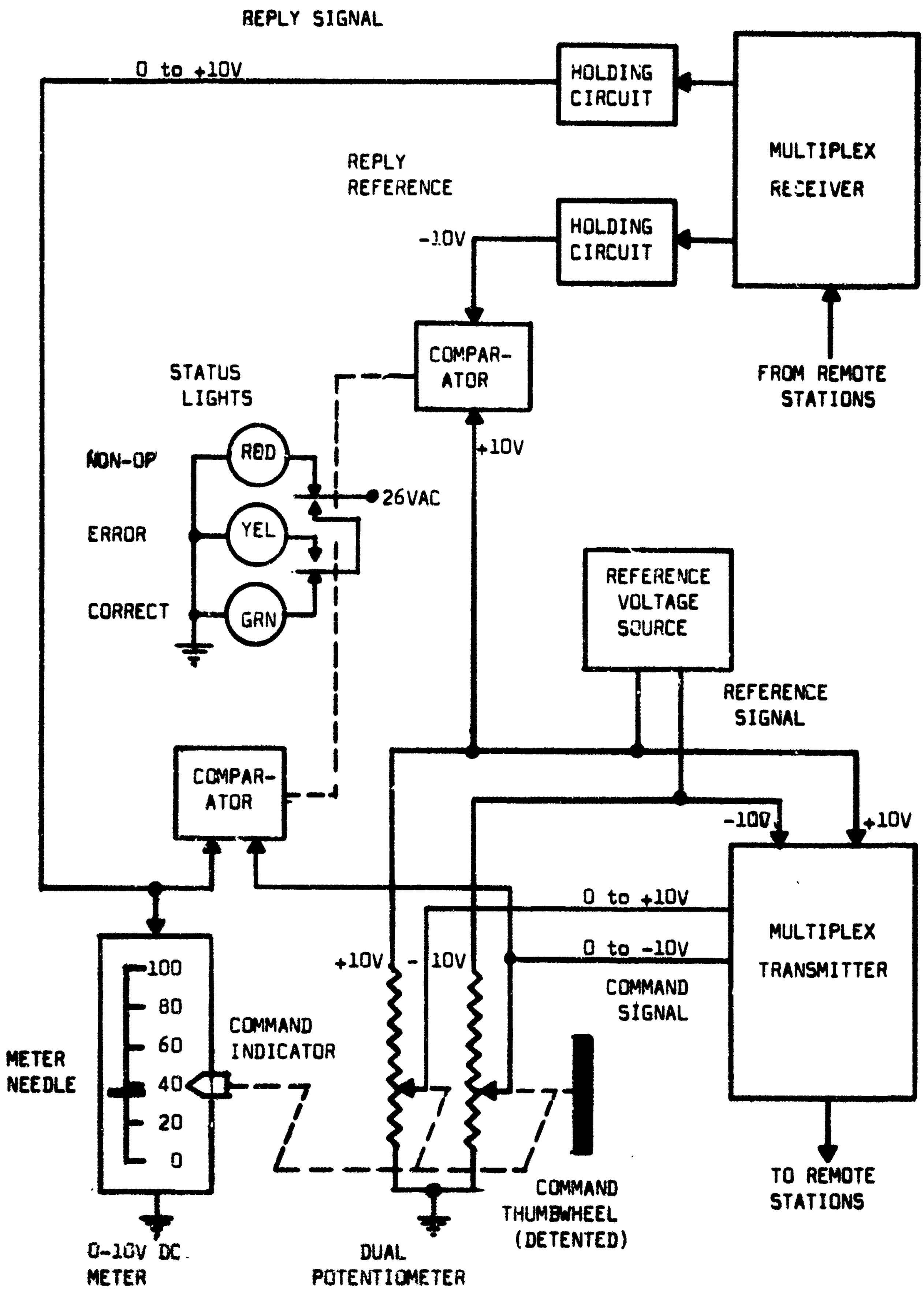

FIGURE 1. MASTER STATION INPUT/OUTPUT TECHNIQUES

If a discrepancy does exist, an error relay will turn on the yellow alarm lamp, calling the attention of the operator to that particular channel meter. If the command and reply signals are approximately equal the error relay will not operate and o ly the green lamp will glow. A green lamp assures the operator that his commands have been carried out correctly.

The reference voltage source, multiplex transmitter, and multiplex receiver in Figure 1 represent common equipment for channels. All other equipment shown is duplicated for each channel.

(2) Remote Station

Figure 2 illustrates the input/output techniques adopted for each remote station. In the present design, only one data channel is provided at each remote station. The system can be easily expanded, however, to provide more than one data channel per remote station.

The multiplex receiver is designed to extract and demodulate the reference channel and one data command channel of the composite signal received from the master station. The channel assigned to a particular remote station is selectable by means of a 16-position switch. The fixed -10 volts d-c reference voltage and the variable 0 to +10 volts d-c command voltage are stored in output holding circuits to make them appear as continuous d-c voltages. Both reference and command voltages are supplied as external output signals at low impedance. Locally-produced reference signals at $\pm$10 volts d-c are also supplied as output signals.

As a check on channel continuity, the received reference signal is coupled directly to the multiplex transmitter at the remote station for repeat-back to the master station. The received reference voltage is also compared with the local +10 volt reference supply, and if they are not approximately equal, the failsafe relay at the remote station will release. The contacts of the failsafe relay are available for connection to external apparatus in several ways as discussed in the next paragraph.

Either an internal or external reply signal can be selected as the second input signal to the multiplex transmitter. For internal reply, the received command signal is repeated back directly. For external reply, a signal representing the response of lighting equipment to the received command, is applied to the multiplex transmitter.

(3) Failsafe Features

Round-trip transmission of the reference signal to and from each remote station provides a constant channel-by-channel continuity check on the system. Continuity checking is independednt of the amplitude of the command and reply data signals being transmitted.

Any failure in the command or reply circuit for a particular channel will cause the failsafe relay at the master station to release and light the red alarm lamp for that channel. The control operator is therby alerted to the fact that a particular channel is not operating correctly and that corrective action must be taken.

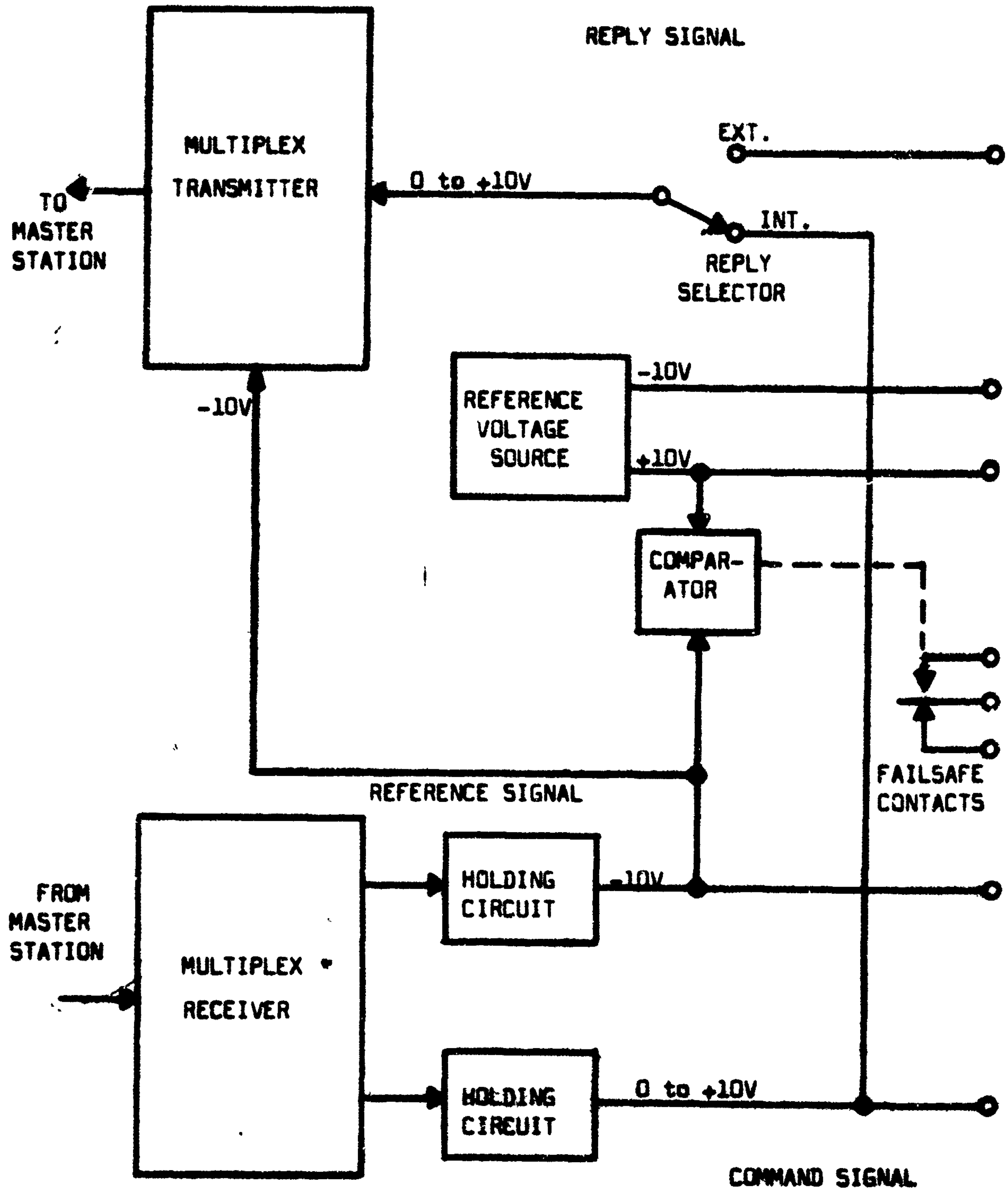

FIGURE 2. REMOTE STATION INPUT/OUTPUT TECHNIQUES

If the failure occurs in the command circuit, the failsafe relay in the affected remote station(s) will also release. In this event, the failsafe contacts can be used to override any received commands and to switch the lighting apparatus being controlled either to a full on or full off condition. The failsafe contacts can also be used to maintain the lighting apparatus at its last commanded brightness by removing power from a servomechanism device having mechanical memory.

Should the failure be of only very brief duration, the electrical memory provided by the output holding circuits will prevent any interruption to normal operation. The holding circuits are designed with a discharge time constant of 10-15 seconds.

Special failsafe features have also been designed into the multiplex receiver and transmitter equipments to protect against specific kinds of failure. If no r-f signal is received at any of the multiplex receivers, for example, the demodulation circuits are disabled to prevent noise from reaching the output circuits. In addition, the remote station receiver contains provisions for disabling the demodulation circuits if synchronism with the master station has not been established. Furthermore, a remote station transmitter can be actuated only if valid signals are being demodulated by its companion receiver.

(B) System Timing

Timing relations for the wireless control system are illustrated in Figure 3. All stations transmit on the same r-f frequency on a time-shared basis. Although the experimental system contains only three remote stations, system timing has been designed to accommodate up to 16 remote stations.

Since a response from each remote station is desired within 1 second, an overall frame rate of 1 cps was chosen. The 1 second frame interval is divided into 16 equal intervals, each interval of 1/16 second being associated with a particular remote station. In the present design, each 1/16 second interval is also associated with a particular channel of the system. If more than one channel were provided at a remote station, the system could still accommodate up to 16 remote stations with no change in timing.

The master station transmits repetitively at a 16 cps rate. Modulation is applied only for 20% of the cycle, or for an interval of 1/80 second. To prevent switching transients from interferring with the modulation, the r-f carrier is turned on for approximately a 1/40 second interval which brackets the modulation interval.

The composite modulation signal at the master station can contain up to 17 subcarriers (16 channels plus reference). In the experimental system, however, only 3 channels plus refernce are used. Each remote station receives repetitive signals on its assigned subcarrier at a 16 cps rate. It also receives the reference subcarrier at a 16 cps repetition rate.

To cause each of the remote stations to reply at the proper time, the modulation on each data subcarrier is switched from a command (0 to +10 volts modulation) to a query (-10 volts modulation), once every second. Thus in each one second interval, each remote station receives 15 commands and one query. The remote stations are queried in time sequence; and reply to the master station in the same sequence.

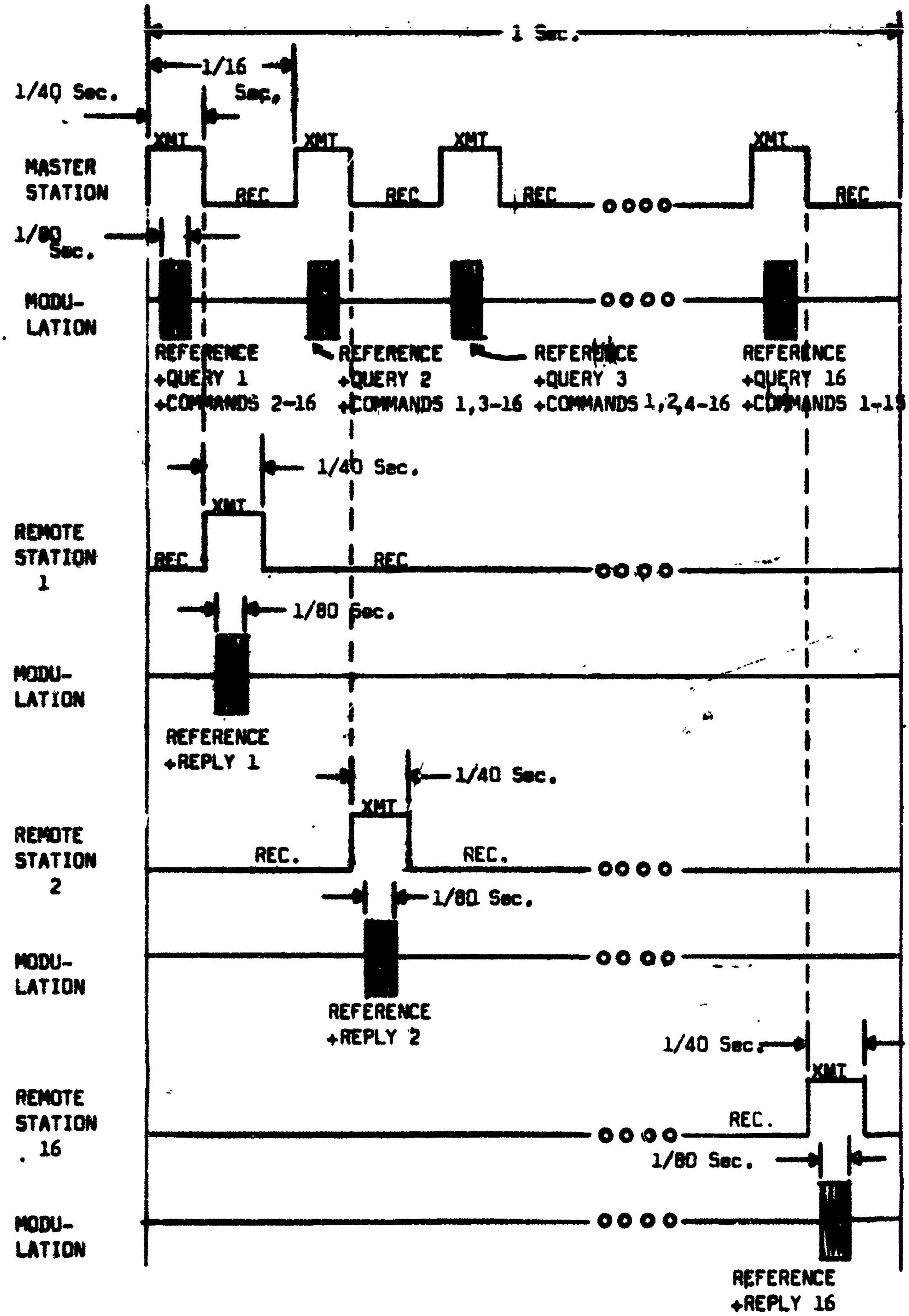

FIGURE 3 SYSTEM TIMING

The timing at each remote station is slaved to that of the master station by means of automatic frequency control (AFC) techniques. The reference signal broadcast as a part of each master station transmission provides the necessary timing reference, independent of modulation on the data channels.

When each remote station receives a query signal on its assigned subcarrier, it will reply 1/80 second later. Its modulation signal also lasts for 1/80 second, and contains a repeat-back of the reference signal plus a modulated data reply on its assigned subcarrier. The remote station r-f signal is turned on for approximately a 1/40 second interval which brackets the reply modulation interval, and follows almost immediately after the turn-off of the master station carrier. A remote station will transmit only if it has been properly queried. Special failsafe protection circuits have been incorporated to eliminate spurious reply transmission.

Even though a remote station has locked into synchronism, its reply signal will not be received at the master station exactly 1/80 second after the end of the corresponding query. There will always be some additional delay due to the propagation delay and the finite bandwidth of the r-f equipment (approximately 3.5 kc). Of these two factors, equipment delay is the more significant by far. Round-trip equipment delay was found experimentally to be about 700 μs, while the two-way propagation delay for a maximum range of 3 miles is only about 30 μs. A single delay compensation circuit in the master station can therefore be used satisfactorily for receiving from all remote stations, regardless of their range. Since the master station timing oscillator operates at 2560 cps, the required 700 μs timing delay for synchronous reception represents about 1.75 periods of the oscillator frequency. The circuits developed to switch the master station from normal timing for transmitting to delayed timing for receiving are described in detail later.

(C) Multiplexer Design

(1) The ORTHOMUX Technique

One of the unique features of the wireless control system designed on this contract is the use of a previously developed technique of multiplex modulation/demodulation known as ORTHOMUX[1] (patent pending). The technique makes use of orthogonal pulse waveforms as subcarrier signals. The subcarrier waveforms can be generated by means of simple digital circuits, and exhibit a high degree of bandwidth efficiency. All subcarrier signals are transmitted simultaneously with independent amplitude modulations. At the receiving terminal, the data channels are separated and demodulated by means of a correlation process which is optimum for rejecting noise, crosstalk, and interference. By reserving one channel for a timing reference signal, the receiving circuits can automatically be synchronized by simple and reliable AFC circuits.

Compared to more conventional techniques of multiplex modulation/demodulation, ORTHOMUX exhibits a unique combination of efficiency, flexibility, reliability, and low cost. Unlike frequency division multiplexing with AM or FM tones, all subcarriers are derived from a single oscillator

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1. A. H. Ballard "Telemetry Multiplexing with Orthogonal Pulse Waveforms", Paper 10-2, Proceeding of National Telemetering Conference, 1963.

with digital-type circuits, thereby minimizing the use of bulky inductors and the associated problems of frequency stability. Higher spectrum efficiency is obtained than with tone multiplexing because crosstalk is eliminated without the waste of spectrum guard bands between channels.

Unlike conventional time-division multiplex techniques, all the channels are transmitted simultaneously, and the problems of automatic synchronization are greatly simplified. For channel accuracy of a few percent, ORTHOMUX is much more efficient in bandwidth utilization than either PCM or PDM. ORTHOMUX is also more efficient than PAM since the PAM data rate for a given bandwidth would have to be reduced to achieve an acceptable level of crosstalk.

(2) Subcarrier Signals

Figure 4 illustrates the orthogonal pulse subcarrier waveforms chosen for this application. All are binary waveforms having a (normalized) amplitude of ± 1, and a common repetition rate of 80 cps. Each waveform, designated as P_n, starts at the +1 level and during each repetition interval ($T=1/80$ second) undergoes a number of polarity reversals equal to its index number n.

Where the index number is an exact power of two, the waveform transitions occur at odd multiples of T/2n, as in the following chart:

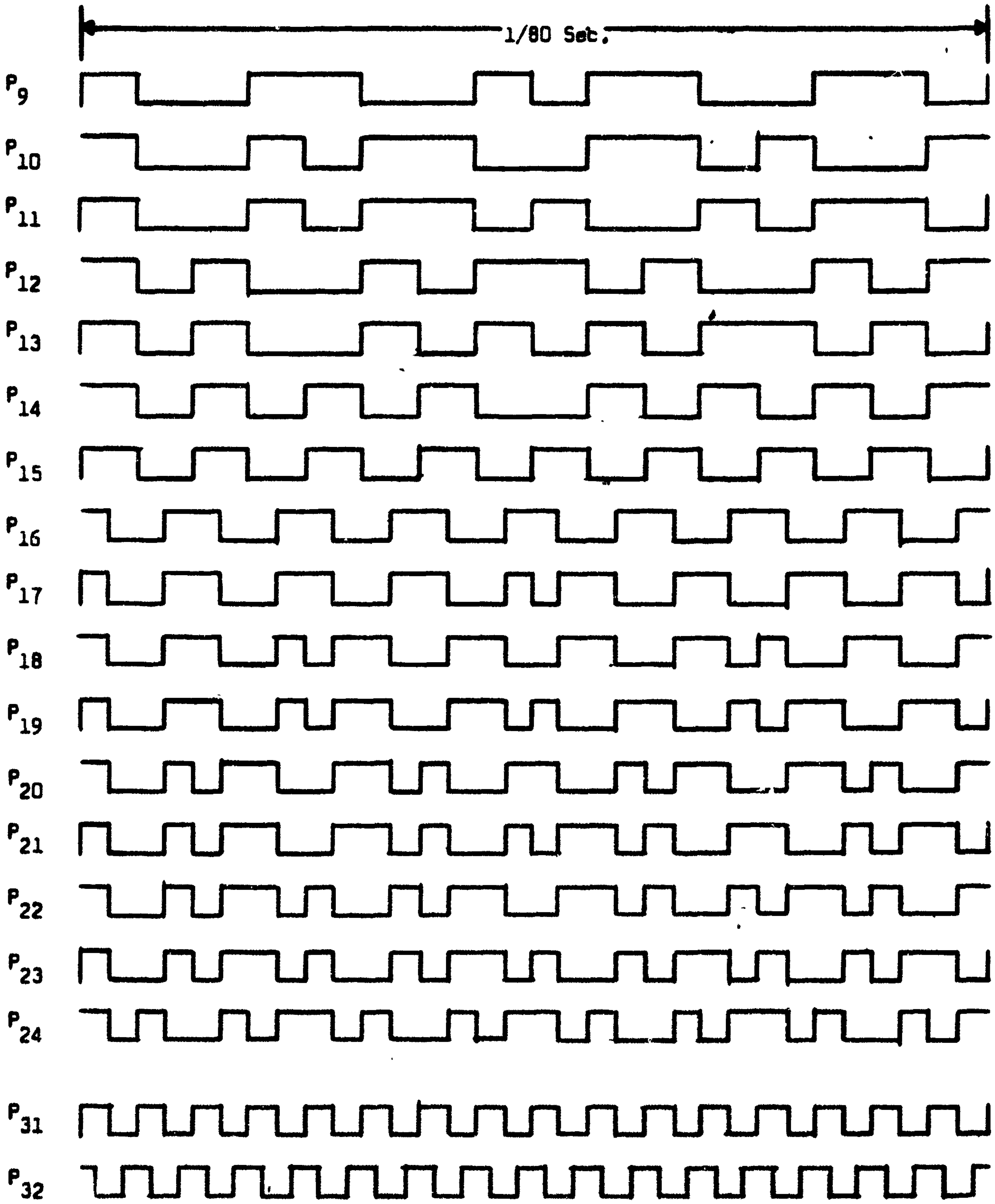
P_n	Transition Points	
P_1	T/2	Not shown in Figure 4
P_2	T/4 (1, 3)	
P_4	T/8 (1, 3, 5, 7)	
P_8	T/16 (1, 3, 5, 7, 9, 11, 13, 15)	
P_{16}	Odd multiples of T/32	
P_{32}	Odd multiples of T/64	

Where the index number is not an exact power of two, the waveform transitions consist of binary combinations of those in the chart. Thus P_9 combines the transitions of P_8 and P_1 because in binary notation, $9 = 2^3 + 2^0$. Similarly P_{10} combines the transitions of P_8 and P_2; P_{11} combines the transitions of P_8, P_2, and P_1; and so on. In theory, this set of waveforms could start at $n = 0$ and be extended to higher index numbers ad infinitum. The waveforms illustrated in Figure 4 were chosen as subcarriers for this system because of their frequency spectrum characteristics as discussed later.

The pulse waveforms in Figure 4 have the property of being mutually orthogonal, which means that they obey the mathematical law:

$$\frac{1}{T}\int_0^T P_n(t)P_m(t)dt = \begin{cases} 0 \text{ if } m \neq n \\ 1 \text{ if } m = n \end{cases} \qquad (1)$$

Thus the product of any two different waveforms in an orthogonal set averages to zero. The product of any waveform times itself averages to unity, if its amplitude is suitably normalized. That the waveforms of Figure 4 satisfy equation (1) above, can be verified by visual inspection.



ALL AMPLITUDES = ± 1 (NORMALIZED)

P_{31} = 0° REFERENCE SUBCARRIER

P_9 THRU P_{24} = DATA SUBCARRIERS

P_{32} = 90° REFERENCE SUBCARRIER

FIGURE 4 SUBCARRIER WAVEFORMS

The product of any pair averages to zero, because they will always be equal in polarity for one half of the interval T and opposite in polarity for the remaining half. Each waveform also has a mean square value of unity because its normalized amplitude is always ± 1. It is their property of being orthogonal which permits these subcarriers to be separated and demodulated without interaction in the receiving portions of the system. Although many sets of orthogonal waveforms exist, the pulse waveforms chosen have the advantage of being easily generated and detected by simple, digital-type circuits.

The frequency spectrum corresponding to the 16 data subcarriers P_9 through P_{24}, and the reference subcarriers P_{31} and P_{32}, are shown in Figure 5. The spectrum for each subcarrier, when unmodulated, can be computed as:

$$F_n \left(\frac{k}{T}\right) = \left| \frac{1}{T} \int_0^T P_n(t)\, e^{-j\frac{2\pi kt}{T}}\, dt \right| \qquad (2)$$

A line spectrum at discrete multiples of 80 cps is obtained with no modulation. In the presence of amplitude modulation, the energy spreads out into symmetrical side-bands extending 80 cps on either side of the lines shown.

As shown in Figure 5, the spectrum for each odd numbered waveform is the same as for the next higher even numbered waveform, since they differ only in phase. Each even numbered waveform P_n exhibits a spectrum peak at the $k = n/2$ harmonic of 80 cps. Spectrum peaks for the data subcarriers range from 400 cps (P_9 and P_{10}) to 960 cps (P_{23} and P_{24}). The reference subcarriers (P_{31} and P_{32}) exhibit a spectrum peak at 1280 cps. All of these waveforms can be passed easily through a nominal 300-3000 cps audio bandwidth.

All of the waveforms contain higher harmonics of 80 cps which decrease beyond the spectrum peak at a rate of 6 db per octave. These higher harmonics, which arise from the sharp edges and corners in the original pulse waveforms, do not have to be preserved to maintain an acceptable amount of orthogonality. Experience has shown that a system bandwidth equal to twice the highest spectrum peak (2560 cps in this case) is sufficient to maintain crosstalk levels down about 40 db (approximately 1% of full scale).

(3) Modulation/Demodulation

Information is conveyed in an ORTHOMUX system by multiplying each subcarrier P_n with an associated modulation voltage a_n. The multiplication process is equivalent to double-sideband amplitude modulation, and because of the binary nature of the subcarrier waveforms, can be accomplished by simple diode switching circuits. The composite signal obtained after linear addition of the modulated subcarriers can be expressed as:

$$E(t) = \sum_{N_1}^{N_2} a_n P_n(t) \qquad (3)$$

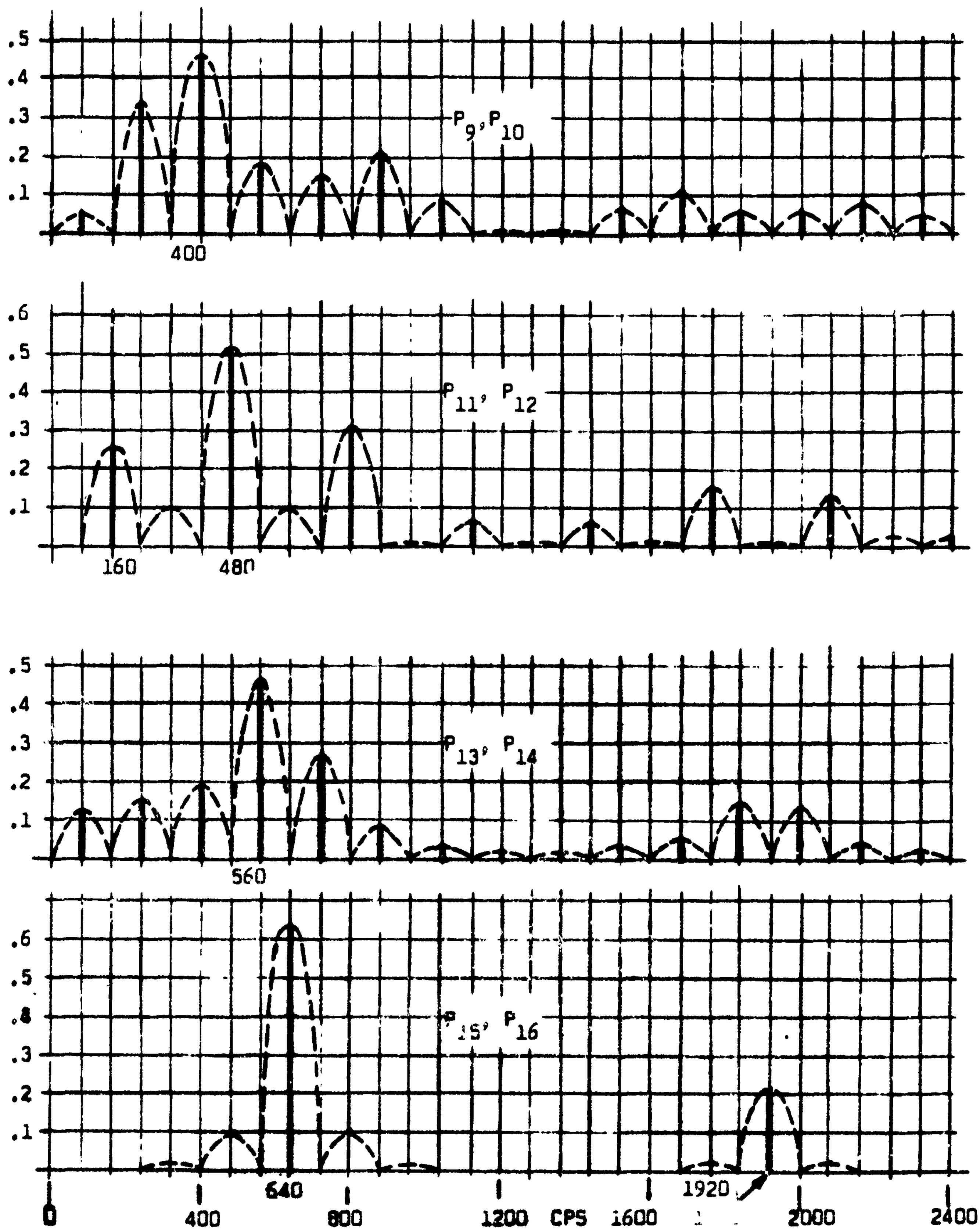


FIGURE 5 FREQUENCY SPECTRUM OF SUBCARRIER WAVEFORMS

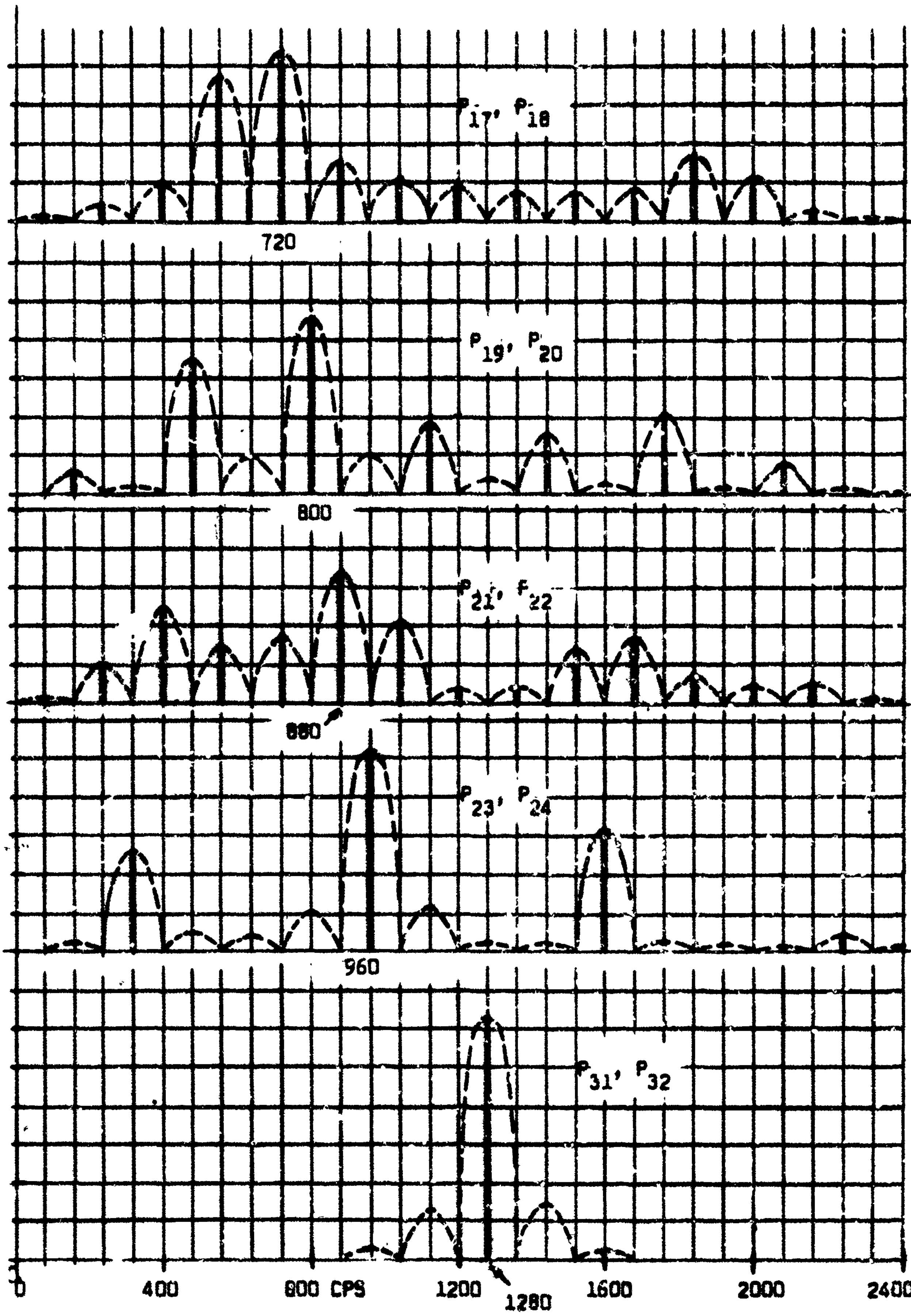


FIGURE 5 (cont) FREQUENCY SPECTRUM OF SUBCARRIER WAVEFORMS

In this particular application, the modulating voltage a_n ranges from 0 to +10 volts for a command or reply, and is equal to -10 volts for a query. A constant +10 volts modulation is always used for the reference channel. During any given repetition interval T, the modulation voltages a_n remain essentially constant, thereby assuring that the subcarrier waveforms remain orthogonal.

After transmission over an r-f link, the composite signal is demodulated for each channel by means of a correlation process:

$$a_m = \frac{1}{T} \int_0^T E(t)P_m(t)\, dt \tag{4}$$

That is, the modulation voltage for a particular channel is extracted by multiplying the received composite signal by the subcarrier waveform associated with that channel, and integrating with the proper scale factor. Equation (4) can be verified if E(t) is replaced by the sum of terms given in equation (3). All product terms having unequal subscripts average to zero by virtue of equation (1), while the product term $a_m P_m(t) P_m(t)$ averages to a_m.

Figure 6 illustrates the modulation and demodulation processes just described in terms of typical waveforms. In the example chosen, the P_9 subcarrier is modulated at negative full-scale (inverted) representing a query. The P_{12} subcarrier is modulated at one-half positive full scale representing a data command. The composite signal is a complex pulse waveform exhibiting four different amplitude levels.

The same composite waveform is recovered at the receiving terminal. (Waveform rounding and delay which would occur in practice have been omitted for clarity.) At the receiving terminal, multiplication of the composite signal by a local P_9 waveform gives a product signal whose average value is -1. Integration of the product signal gives a negative-going sawtooth waveform which reaches the value -1 at the end of the interval T. Only the d-c component of the product signal affects the final integrated voltage. Other components of the product signal always integrate to zero. In a similar manner, multiplication of the composite signal by a local P_{12} waveform gives a d-c component of +0.5 in the product signal, which can be extracted by integration. Demodulation using a local P_{23} waveform, on the other hand, gives a zero result.

The noise bandwidth of a correlation detector such as this depends only on the integration time T. Assuming additive Gaussian noise of uniform spectrum, the noise bandwidth of each channel demodulator will be 1/2T, or 40 cps in this case.[2]

(4) Automatic Synchronization

Correct operation of the demodulation circuits requires that the timing of the locally-generated subcarrier signals

2. W. B. Davenport and W. L. Root, Random Signals and Noise, McGraw-Hill 1958

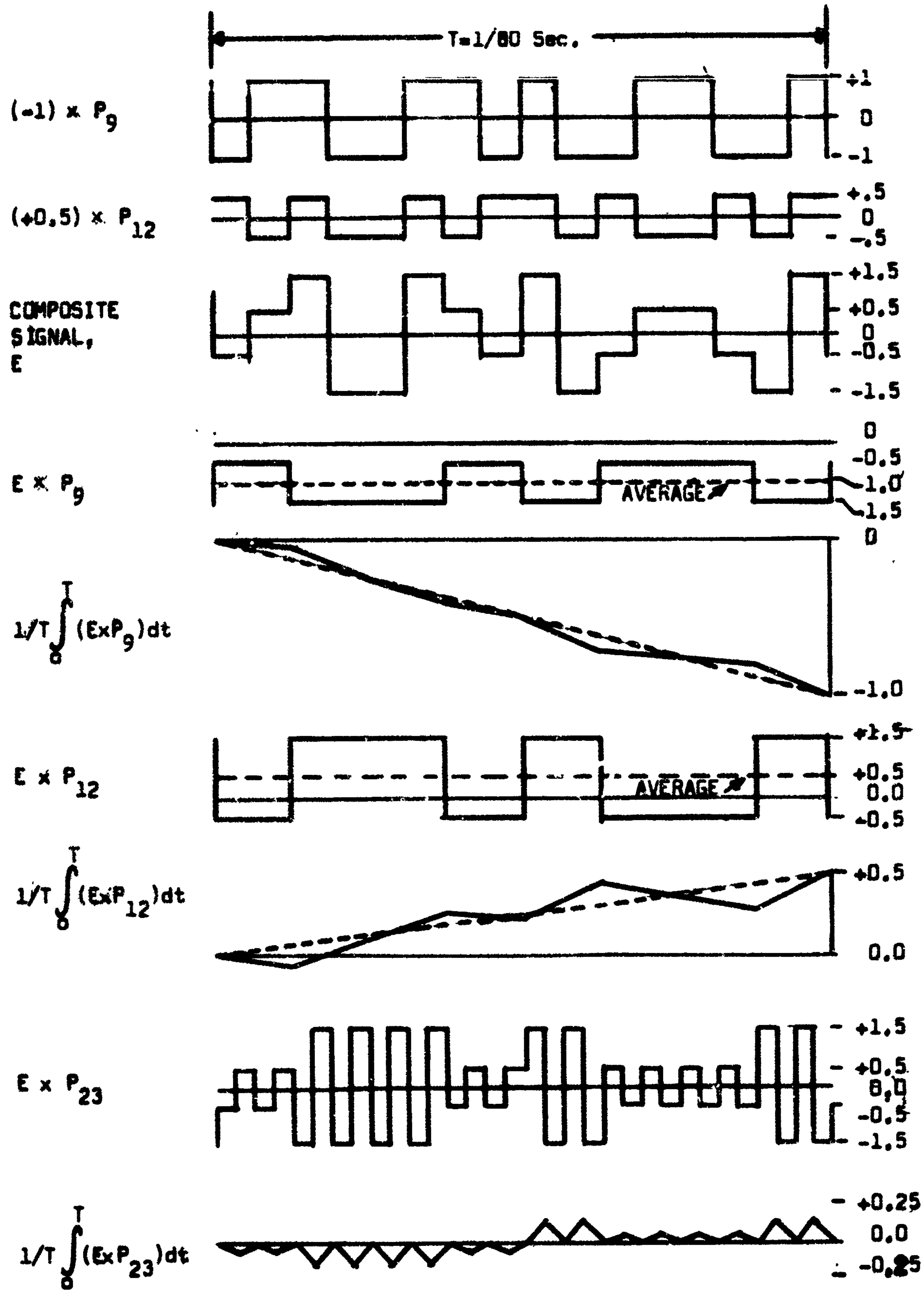


FIGURE 6 MODULATION AND DEMODULATION

be accurately synchronized to the received composite signal. For this reason, the P_{32} waveform is broadcast as a part of each master station transmission. It acts as a timing reference for automatic synchronization of all remote station timing oscillators.

Figure 7 illustrates the techniques employed at each remote station for automatic synchronization. The local timing oscillator operates at a nominal frequency of 2560 cps. After suitable shaping, the oscillator signal triggers a flip-flop to produce a 1280 cps square wave. This signal is the local P_{31} reference waveform. It is applied to a switching-type multiplier, the other input of which is the received composite signal.

Only the P_{32} reference component of the composite signal is shown in Figure 7 for clarity. The other subcarriers when multiplied by the local P_{31} waveform will always have an average product of zero even though a timing error exists. If the local oscillator frequency is slightly low, the P_{31} waveform will be slightly delayed from its correct position and the multiplier will produce a positive average voltage. If the local oscillator frequency is slightly high, the P_{31} waveform will be slightly advanced from its correct position and the multiplier will produce a negative average voltage.

The average voltage of the multiplier signal is extracted by means of a low pass filter and applied as an AFC voltage to the local oscillator. The polarity of the AFC voltage is such as to pull the oscillator frequency in the direction which will correct the timing error and reduce the average multiplier voltage to zero. A double time-constant low-pass filter was found to give the best dynamic performance of the AFC loop. A long time constant of several seconds provides memory over many 16 cps transmissions of the timing reference. A shorter time constant is also used to superimpose the average voltage over a single reference burst, to aid in achieving rapid pull-in. It was found experimentally that if the pull-in range of frequency was made too wide, the local oscillator could also lock on frequencies spaced at multiples of 16 cps away from 2560 cps. This phenomenon arises because the timing reference occurs in bursts, and is in effect modulated at a 16 cps rate. It is possible therefore for the local oscillator to lock onto the sideband frequencies of the modulated reference signal. To minimize the possibility of false locking, the natural frequency of the oscillator was stabilized to drift no more than about 8 cps on either side of 2560 cps.under all environmental conditions. Accurate pull-in was achieved from approximately 10 cps on either side of 2560 cps. In the event that the oscillator does lock onto an incorrect frequency, this condition will be detected in a failsafe manner by the out-of-sync detector described below.

The AFC circuits just described should bring the local oscillator and P_{31} flip-flop into accurate synchronism. The AFC voltage vs delay error curve exhibits ambiguities every 1/1280 second, however, and the lower speed counters can still be delayed by some multiple of 1/1280 second relative to the received composite signal.

The timing reference for the lower speed counter flip-flops is taken from the turn-on time of the master station r-f carrier. When the r-f carrier turns on, (slightly before the start of modulation), the remote

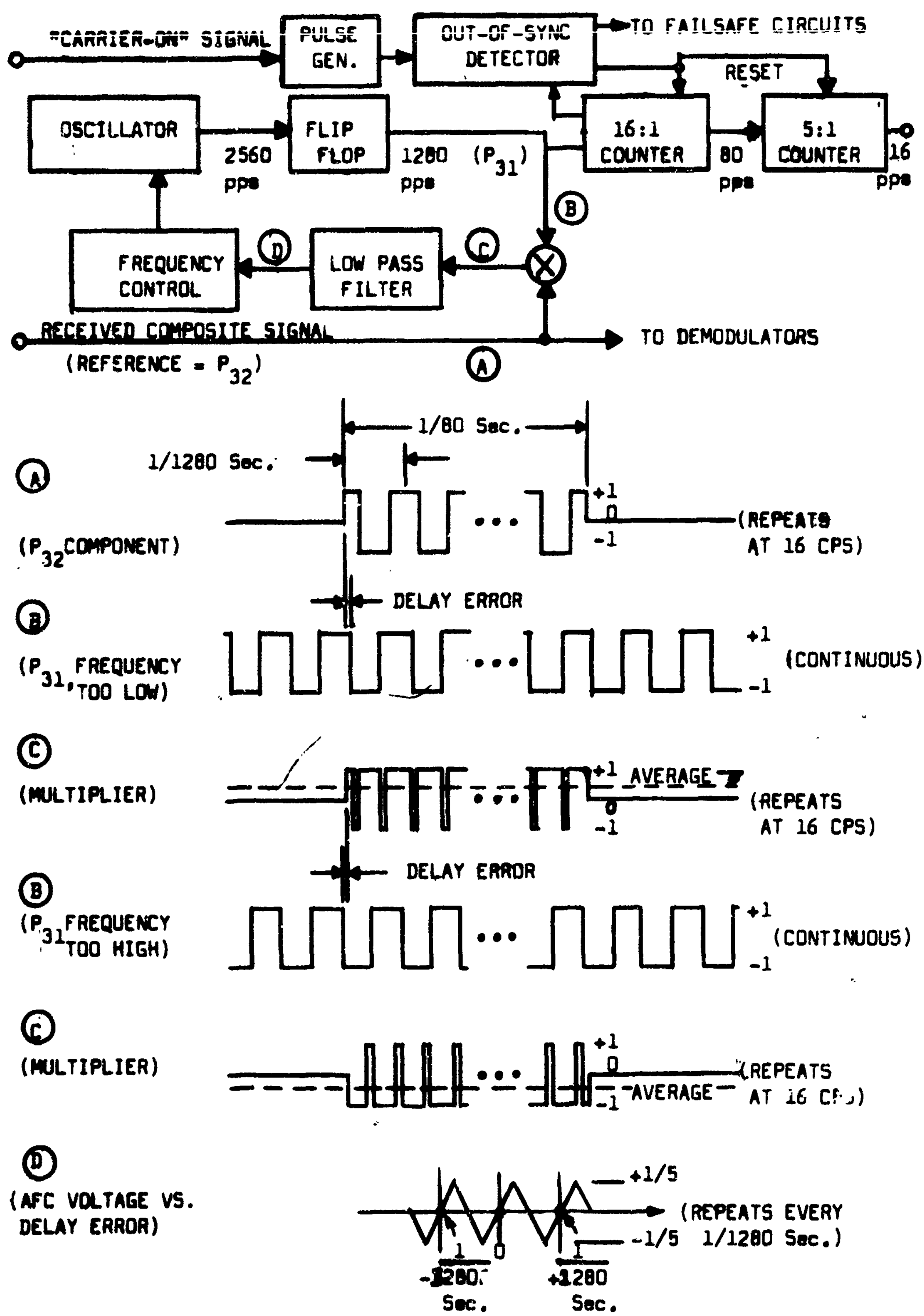


FIGURE 7 SYNCHRONIZATION OF REMOTE TIMING

station counter flip-flops should be in a known state. A coincidence circuit in the out-of-sync detector is used to determine whether or not the flip-flops are in the correct state at that time. If the timing is correct, an integrating capacitor is charged to present an "in-sync" voltage indication to the failsafe circuits. If the timing is not correct, the integrating capacitor will discharge until its voltage drops below the "out-of-sync" threshold. A reset pulse is then generated to force the counter flip-flops to their correct state. The circuits used for this purpose are described in greater detail later.

(D) R-F Design

An r-f frequency in the 162-174 mc band was specified in the original requirements. This band is available for fixed or for mobile ground communications, when applied for public safety or industrial use. A total emission bandwidth of 16 kc was specified, because channel allocations are spaced by 30 kc in this band. The actual frequency used in this system (162.225 mc) was selected by the FAA, and an experimental license was obtained from the FCC to use this frequency for one year in the Washington, D. C. area.

FM modulation of the r-f carrier is normally used in this band, and was considered to be highly desirable for this application. The use of FM makes the system highly resistant to noise, interference, or fading and virtually eliminates any need for system calibration as a function of range or propagation conditions.

A maximum deviation of 5 kc was established for the Wireless Control System to insure an r-f emission bandwidth of 16 kc or less. This maximum deviation must of course be distributed among all of the multiplexed channels of the system. To provide a capacity of 16 channels plus reference, the deviation per channel must be held to approximately 0.3 kc. In contrast to voice communication systems, the maximum modulating voltage of the composite signal in the Wireless Control System is pre-determined by circuit design.

Figure 8 illustrates in simplified form the r-f spectrum which would be obtained for a 3-channel and a 16-channel system. In the case of 3 channels plus reference, maximum deviation is assumed to be 1.25 kc. The modulation is assumed to be a 1.28 kc sine wave (spectrum peak of the highest frequency subcarrier P_{32}). Deviation ratio is approximately unity, and the spectrum curve, plotted from standard Bessel functions is a single narrow lobe lying well within the allowed bandwidth of 16 kc. In the case of 16 channels plus reference, the same assumptions have been made except that the maximum deviation has been increased to 5 kc. Deviation ratio is approximately 4 in this case, and a three-lobed Bessel curve is obtained. In practice of course, a single broad flat spectrum would be obtained because of the many lower frequency components present in the composite modulating signal. The r-f spectrum will still be well within the allowed 16 kc band, however.

A maximum power output of 10 watts was selected from considerations of propagation loss at the maximum system range of 3 miles. The curves in Figure 9 show how path loss varies with distance at 160 mc for propagation in free space and for propagation near a plane earth[3]. The second curve is

3. H. Jasik, Antenna Engineering Handbook, McGraw-Hill, 1961

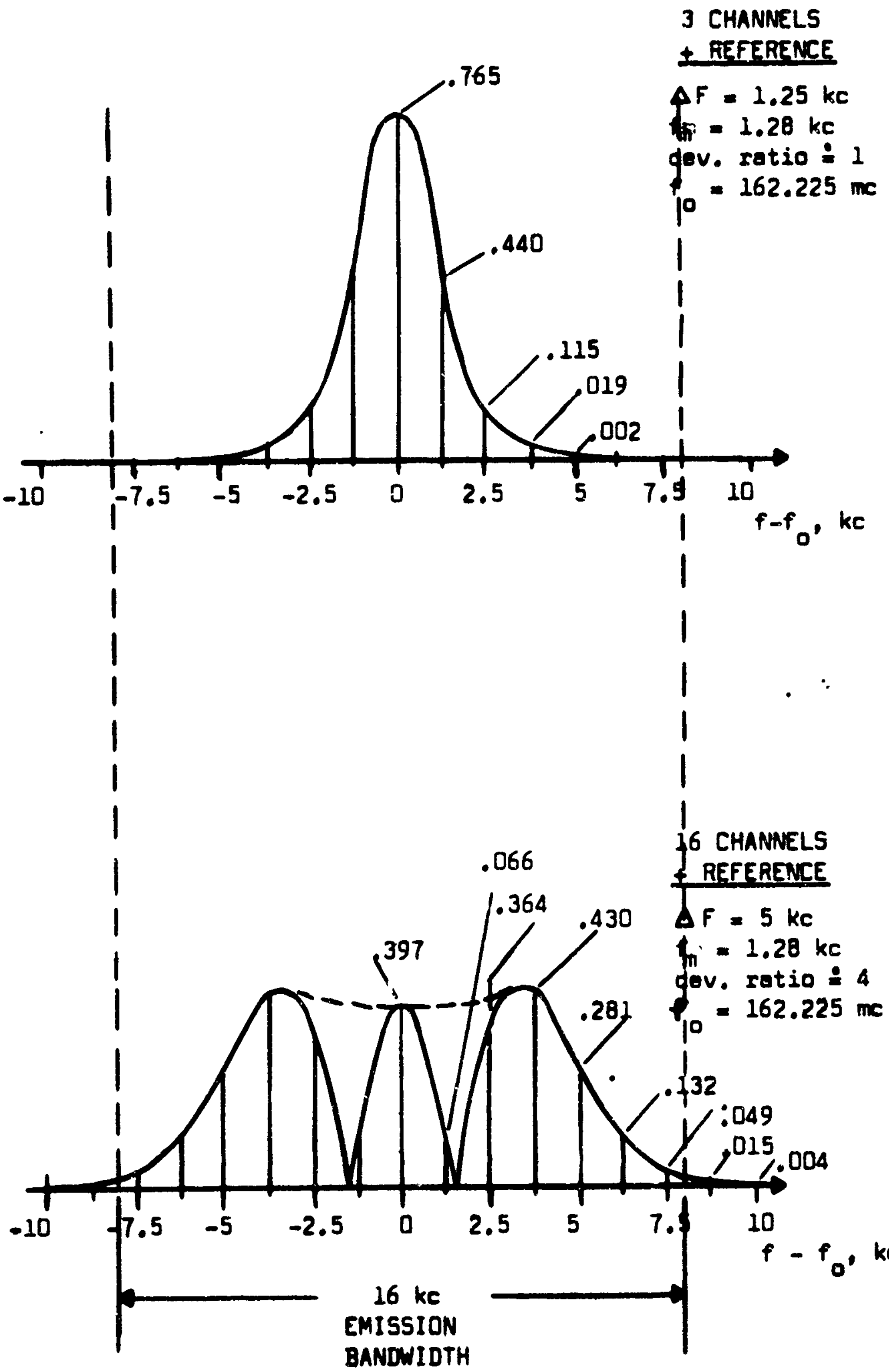


FIGURE 8 R-F SPECTRUM

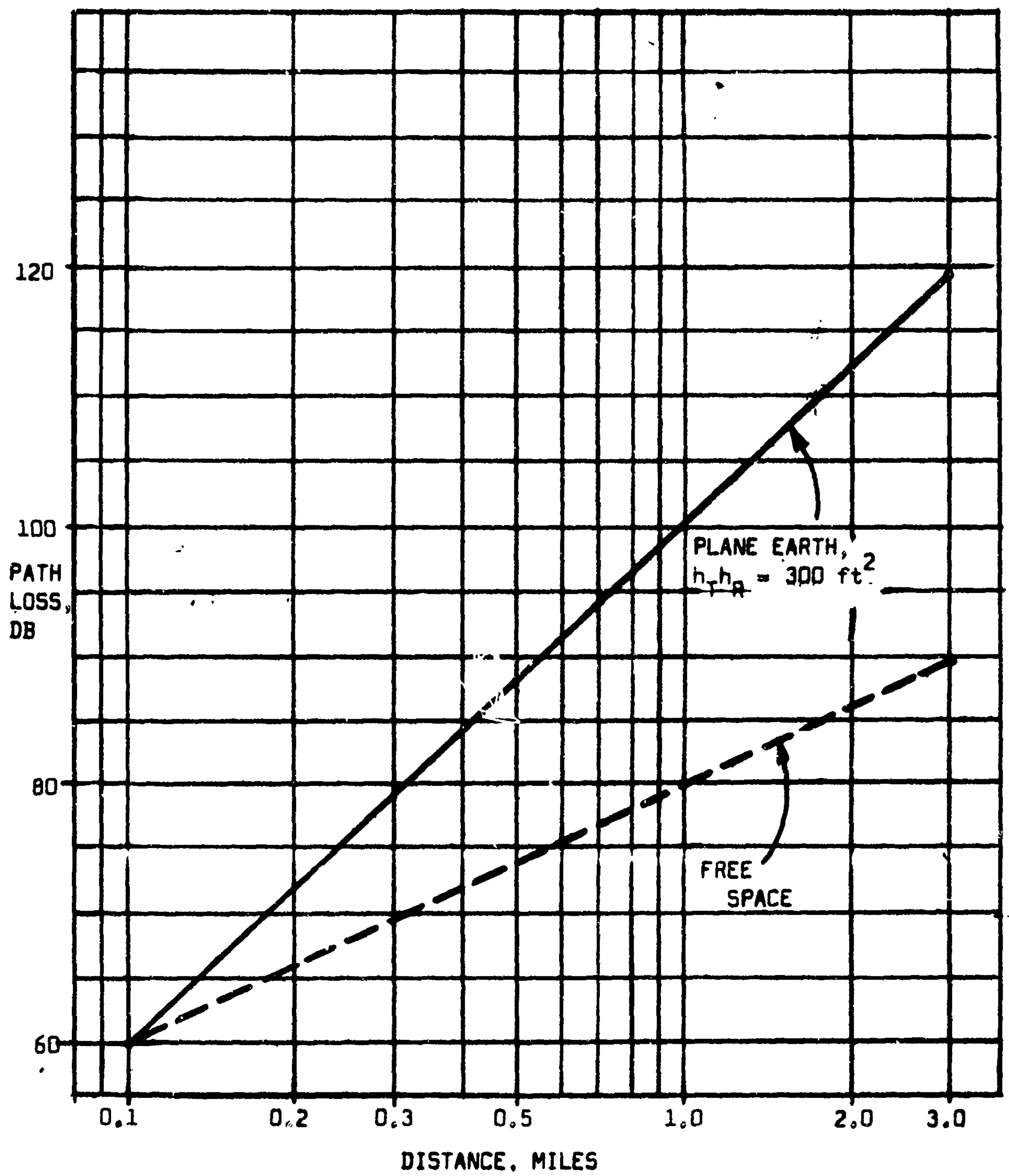


FIGURE 9 R-F ATTENUATION VS DISTANCE

the appropriate one to use in this case, except that the attenuation can never be less than the free space loss. If the antenna heights have a product of 300 feet^2 (30 feet at the transmitter and 10 feet at the receiver, for example), the path loss varies from 60 db at 0.1 mile to 120 db at 3 miles.

Assuming antenna gains of 0 db, a power output of 10 watts from th transmitter would produce a signal level of -80 dbm at a receiver 3 miles away. The corresponding voltage developed across 50 ohms would be approximately 20 microvolts. Since typical receivers have sensitivity of at least 1-2 microvolts, a 20 db margin for the system can be assured.

Several commercial FM transceivers, designed for mobile voice communications but coming very close to the performance desired for this application, were found to be readily available. Among the equipments considered were transceivers manufactured by Motorola, General Electric, and Hammarlund. The one finally selected was the Motorola Conscelette Base Station, Model L43GGB-1100A. The equipment has been certified by the FCC to have the following performance:

Frequency Range	144-174 mc
Frequency Stability	$\pm$0.0005%
Power Output	10 or 25 watts
Spurious Radiation	At least 60 db down
Modulation	0 to $\pm$5 kc, adjustable
Sensitivity	0.5 μv for 20 db quieting
Selectivity	100 db at +15 kc
Spurious Responses	100 db down

After experimenting with a pair of these equipments, it was found that the following changes were required for successful incorporation into the Wireless Control System:

1. The audio input amplifier and pre-emphasis network ahead of the phase modulator were not usable because of the system requirement for a lower frequency response. The pre-emphasis required to obtain frequency modulation from the phase modulator was achieved by an external integrator circuit for the composite modulating signal.

2. The clipper stage at the audio input to the phase modulator was removed because modulating signals in this system already have a predetermined maximum amplitude.

3. The transmit-receive relays used for power supply and antenna switching were replaced by mercury-wetted relays. The latter type of relay is rated for a life of 1 billion operations, which at 16 cps corresponds to almost 2 years of continuous use.

4. The discriminator circuit had to be re-designed to achieve a linearity of 1% over a $\pm$5 kc range.

5. The last 455 kc i-f stage was modified to derive an external "carrier detector" signal from the signal-developed bias voltage in its grid circuit.

6. The audio output stages of the receiver were also found to have a lower frequency response than required for this system and were replaced by external amplifier circuits.

7. Voltage regulator tubes had to be added for adequate power supply stability.

8. The equipment was re-packaged for rack mounting.

DESCRIPTION OF EQUIPMENT

(A) Physical Characteristics

The equipment constructed on this contract consists of one master station (Figures 10 and 11) and three remote station equipments (Figures 12 and 13).

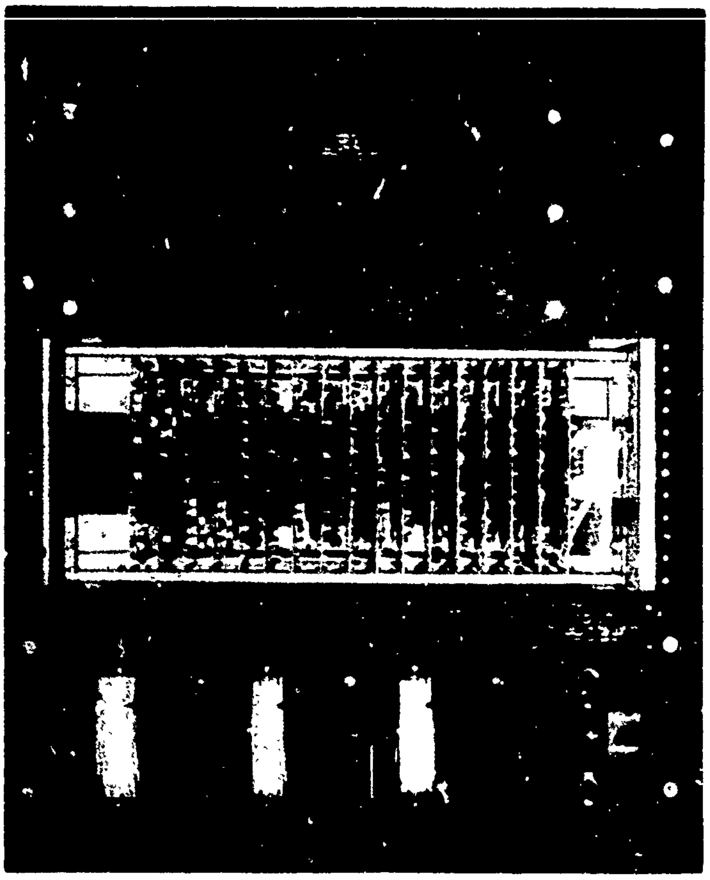
With the exception of its antenna assembly, the master station equipment (Figures 10 and 11) is designed for operation in an indoor environment. It consists of three 7-inch panel assemblies mounted in a standard 19-inch rack. Maximum depth behind the panel, including cable clearance, is 15 inches. Weight of the master station equipment is approximately 75 pounds.

The three assemblies comprising the master station equipment are:

1. A modified commercial FM transceiver (Motorola Consolette Base Station, Model L43GGB-1100A). The audio input/output portions of this equipment have been removed, and the power switches and indicators relocated. An r-f connector at the back of this unit is provided for connection to the remote antenna assembly.

2. A printed-circuit card enclosure with 18 cards, approximately 5" x 6" in size, comprising the transistorized multiplexer circuitry. Nine of these cards contain common circuits which are required regardless of how many channels are used. In addition, three cards are required for each channel used.

3. A combined control unit and power supply assembly which can be separted into two parts. The power supply assembly in the rear furnishes power at +24, +15, -15, and -24 volts d-c to the transistorized multiplexer circuits. Carrier selector switches, for channels 1, 2, and 3 are also located on this assembly. The control unit assembly in the front can be removed and operated remotely from the remainder of the master station equipment. It contains three identical control units for channels 1, 2, and 3, as well as the main power controls and the system standby/operate switch. Located on the front panel of each channel control unit is a brightness setting lever/indicator, a vertically-mounted reply signal meter, red/yellow/green status indicator lamps, and a lamp dimming control.



A. FRONT VIEW

TRANSCEIVER

MULTIPLEXER

CONTROL UNIT ASSEMBLY

B. REAR VIEW

TRANSCEIVER

MULTIPLEXER

POWER SUPPLY

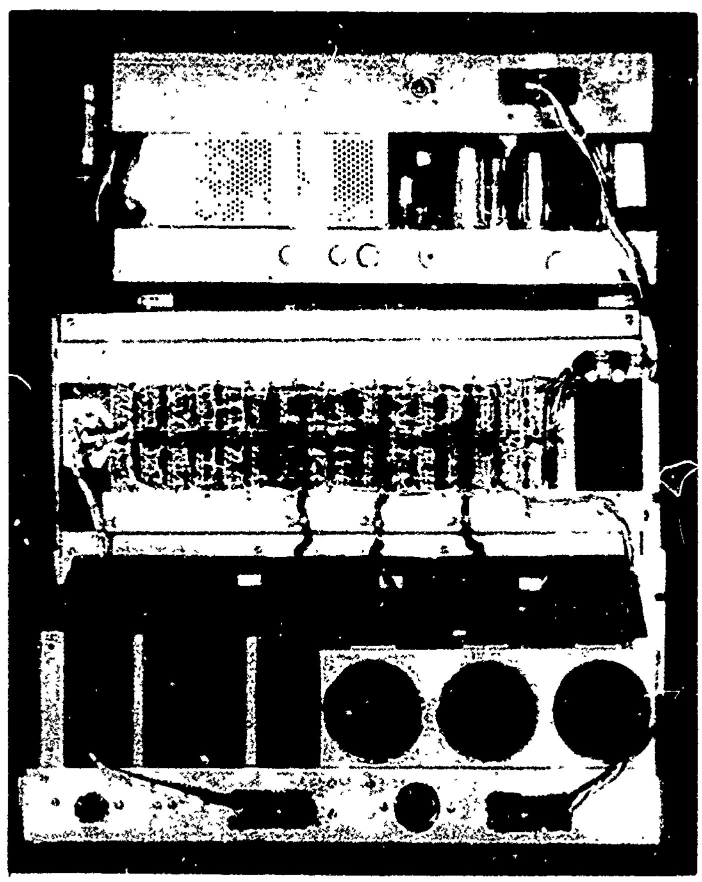


FIGURE 10. MASTER STATION EQUIPMENT

FIGURE 11. CONTROL UNIT ASSEMBLY

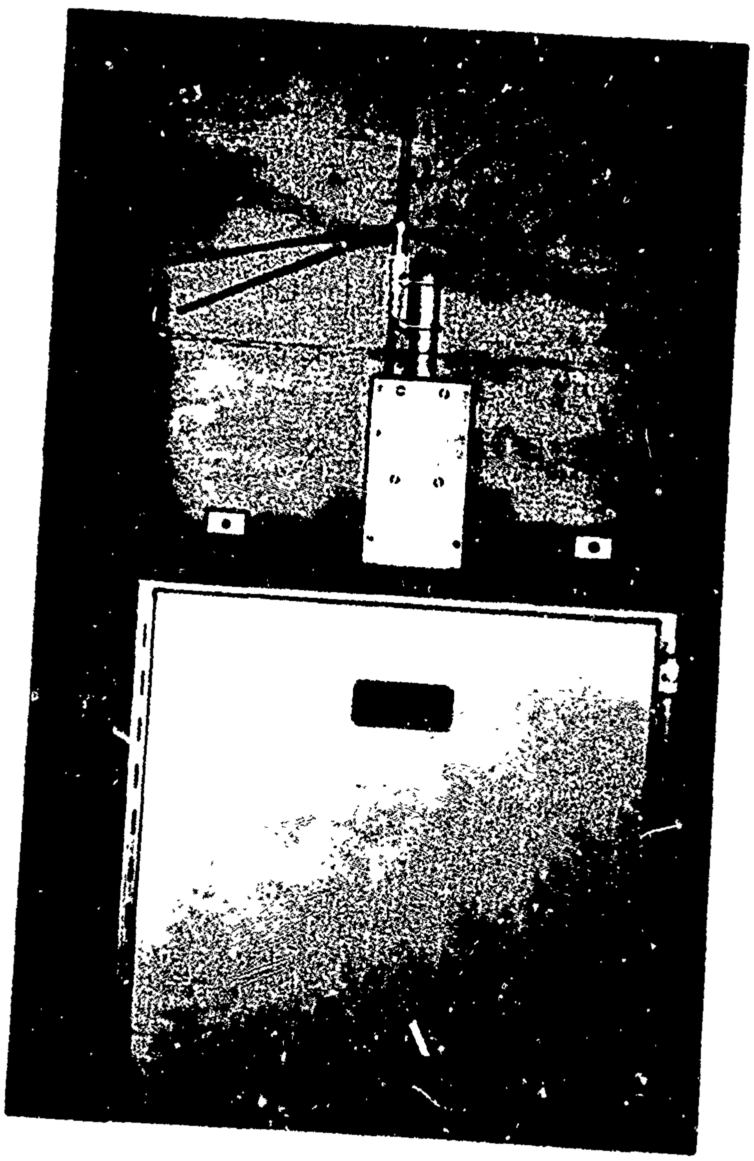


FIGURE 12. REMOTE STATION EXTERIOR VIEW

The remote station equipment (Figures 12 and 13) is designed for operation in an outdoor environment. It is housed in a weatherproof, tamper-proof case whose overall dimensions exclusive of antenna are approximately 27" wide by 35" high by 14" deep. At least 3" clearance is required at the bottom for cables which are brought out through conduits. The remote station equipment exclusive of antenna weighs approximately 115 pounds. It is designed for installation on a wall or post by means of four 1/4" bolts (18" horizontal spacing, 25" vertical spacing). The antenna mast (not supplied) can consist of a 1" D pipe of sufficient height to insure line-of-sight propagation.

When the front door is opened, the three main assemblies of the equipment are accessible for routine alignment and maintenance. These assemblies can also be swung outward on a hinged frame for servicing if necessary. The three electrical assemblies in the remote station equipment are:

1. A modified commercial FM transceiver identical with that in the master station equipment, except that it does not include a time-delay relay in the transmit control circuit.

2. A combined multiplexer and power supply assembly. The transistorized multiplexer is composed of nine printed-circuit boards similar to, and in many cases identical with, those in the master station multiplexer. The power supply circuity is electrically identical with the corresponding unit in the master station.

3. A control panel assembly containing the main power switch and indicator, the carrier selector switch, and internal/external reply selector switch. The failsafe relay and a dual terminal board for external connections are located on the back of this assembly.

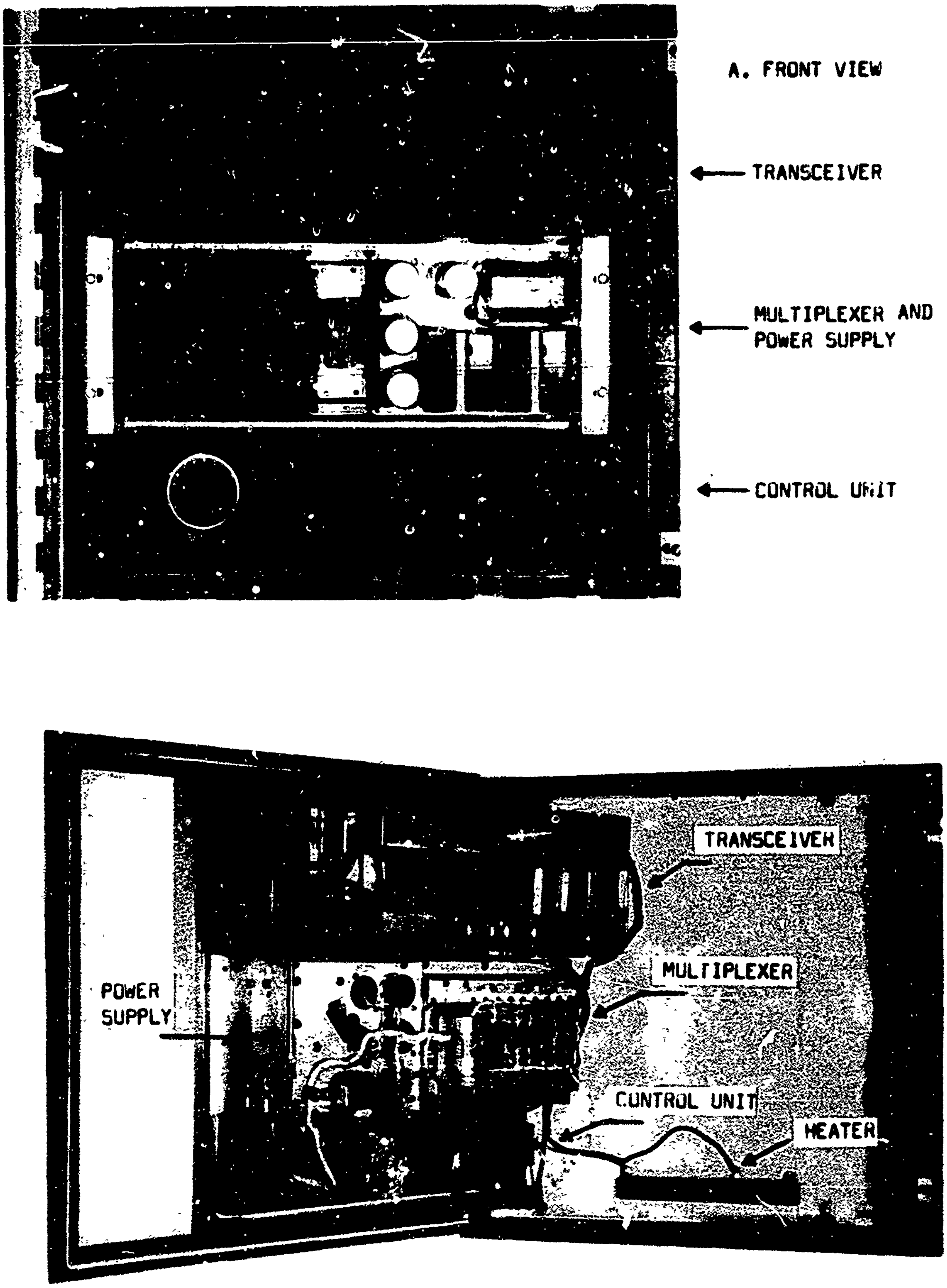
Each remote station equipment is equipped with an internal 75-watt case heater. It is thermostatically controlled to turn on at +10°F and to turn off at +35°F.

(B) Detailed Description - Master Station

A detailed functional block diagram of the master station is shown in Figure 14. Waveforms at significant test points are shown in Figure 15 to explain the operation further.

(1) Timing Circuits

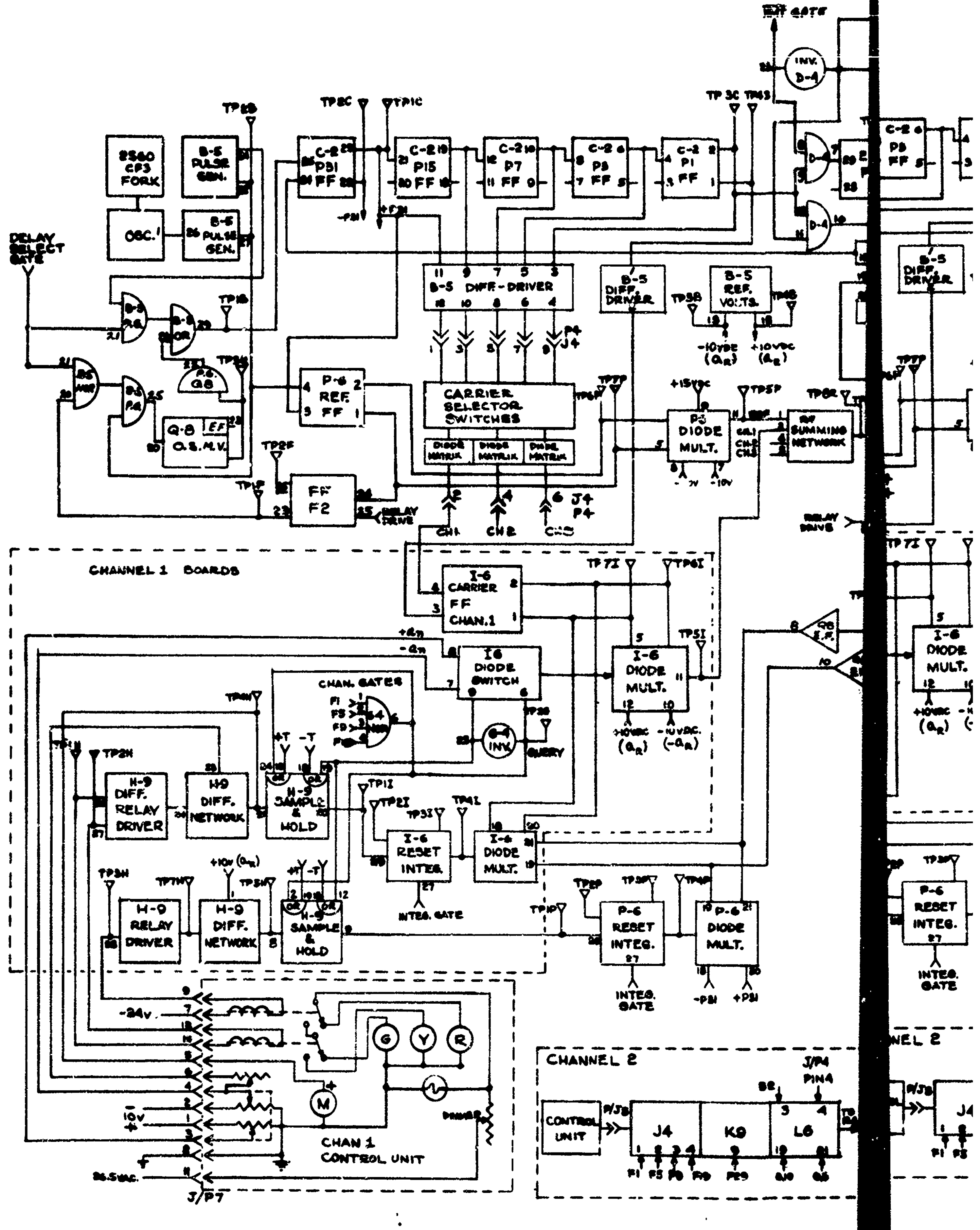
The timing and programming circuits at the top of the diagram represent common equipment needed regardless of the number of channels used. All timing signals are derived from a single oscillator whose frequency, 2560 cps, is controlled by a tuning fork to be accurate within ±0.1%. At the negative zero crossings (180°) of the oscillator signal, pulses are derived (TP-2B) which trigger the reference flip-flop to produce a 1280 cps square wave having a 90° phase shift (TP-7P). This phase-shifted square wave, designated as P32, is included in every master station transmission as a timing reference signal.



A. FRONT VIEW

B. REAR VIEW

FIGURE 13. REMOTE STATION


CHANNEL 1 BOARDS
CARRIER SELECTOR SWITCHES
DIODE MATRIX
B-5 DIFF-DRIVER
REF. FF
O.S.M.V.
DIODE MULT.
DIODE SWITCH
CHAN. GATES
DIFF. RELAY DRIVER
DIFF. NETWORK
SAMPLE & HOLD
RESET INTEG.
RELAY DRIVER
INTEG. GATE
SUMMING NETWORK
REF. VOLTS.
DELAY SELECT GATE
CHAN 1 CONTROL UNIT
CHANNEL 2
CONTROL UNIT
J4
K9
L6
J/P7
J/P4 PIN4
QUERY
RELAY DRIVE
CHANNEL 2

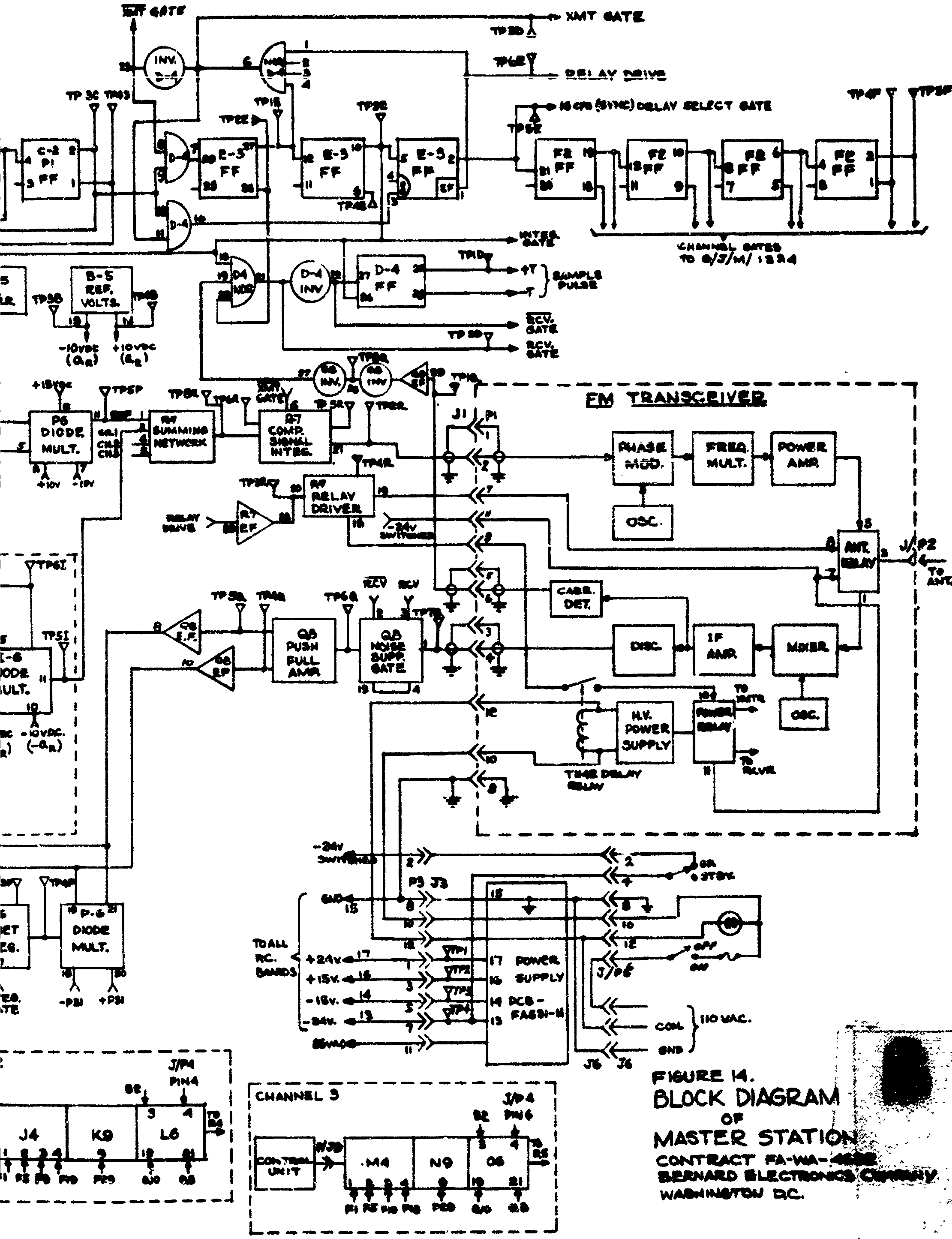
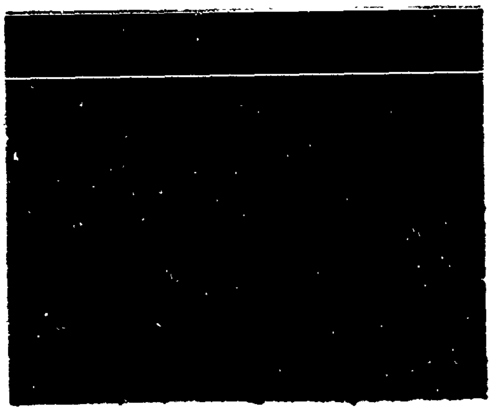


FIGURE 14.
BLOCK DIAGRAM OF MASTER STATION
CONTRACT FA-WA-4[illegible]
BERNARD ELECTRONICS Company
WASHINGTON D.C.



1. P_9 CARRIER TP-7I
(SW. POS. 1, 10V/CM)

2. P_{10} CARRIER TP-7L
(SW. POS. 2, 10V/CM)

3. P_{11} CARRIER TP-7O
(SW. POS. 3, 10V/CM)

4. P_{32} CARRIER TP-7P
(REFERENCE, 10V/CM)

5. COMPOSITE TP-8R
SIGNAL (2V/CM)

6. COMP. SIG. TP-2R
INTEGRATOR (2V/CM)

TIME BASE: 8CM = 1/80 SEC.

FIGURE 15. MASTER STATION MODULATION WAVEFORMS

Pulses are also derived at the positive zero crossings (0^0) of the oscillator signal (TP-1B). The 0^0 pulses drive a chain of five flip-flops, which divide the pulse rate by 32. The output signal from the first of these flip-flops is an unshifted 1280 cps square wave, designated at P_{31} (TP-1C). This signal is used to reset the reference flip-flop to insure that the P_{32} square wave is positive at the 0^0 times. It is also used in demodulating the reply reference signal.

The positive-going edge of each flip-flop waveform triggers the next flip-flop. Output signals are also derived from the negative-going edges of the five flip-flop waveforms which appear as non-overlapping pulses at 1280, 640, 320, 160, and 80 cps. These pulses are applied to the carrier selector switches where they are combined in any of 16 combinations to produce the trigger pulses associated with each of the data carrier waveforms. In addition, a 80 cps reset pulse is derived from the positive-going edge of the last flip-flop waveform (TP-3C) which is used to insure that all data carrier waveforms start with positive polarity. The 80 cps rate is the common repetition rate of all carrier waveforms in the multiplexer, including the reference waveforms.

The 80 cps square wave (TP-3C) is also applied to a chain of three flip-flops, coupled back on itself so as to divide the pulse rate by five. The 5-counter serves to control the transmit-receive cycling of the master station and supplies various 16 cps control signals to other parts of the equipment.

The 5-counter operates in the following way. If continuous pulses were applied, the three flip-flop would step through the eight states;

	1'	2'	3'	4'	5'	6'	7'	8'
TP-1E	0	1	0	1	0	1	0	1
TP-3E	0	0	1	1	0	0	1	1
TP-5E	0	0	0	0	1	1	1	1

In this table, binary 1 = -15 volts and binary 0 = +15 volts. To make the flip-flops count by five, the second state (100) is detected by means of a NOR gate (output = +15V only if all inputs = -15V). The next pulse applied is blocked from the counter input and connected instead to reset the third flip-flop. Thus the counter jumps from state 2' (100) to state 6' (101), and continues thereafter to cycle through the five new states:

	1	2	3	4	5
TP-1E	0	1	1	0	1
TP-3E	0	0	0	1	1
TP-5E	0	0	1	1	1

This sequence permits many of the required 16 cps control signals to be taken directly from the counter flip-flops.

The waveform at TP-5E for example, is used to select either normal timing for transmitting or delayed timing for receiving. The inverted waveform at TP-6E is used as a relay drive signal for transmit-receive switching of the FM transceiver. The XMT gate signal (TP-3D) is used to apply modulation to the FM transceiver only during state 2 of the 5 counter, and is taken from the same NOR gate used for counter re-cycling.

When a reply is received from a remote station, it will occur during state 4 of the 5-counter. The RCV gate signal (TP-2D) is generated by detecting state 4 (011) with an additional NOR circuit. This signal is used to select only the reply portion of the FM discriminator output and to suppress noise or unwanted signals at other times. To prevent noise from entering the demodulation circuits when there is no reply, the RCV gate signal is disabled by the input to its NOR circuit which is connected to the carrier detector signal from the FM receiver.

The INTEGRATE gate signal (TP-3E) allows the demodulation circuits to integrate during state 4 and hold during state 5 of the 5-counter. The sample pulse (TP-1D) is generated during state 5 by an additional flip-flop, provided that reply signal is present. The sample pulse transfers the results of integration to the output data holding circuits.

Compensation for timing delay when receiving is achieved by delaying the 0° oscillator pulses applied to the 32-counter during states 3, 4, and 5 of the 5-counter. The needed delay of about 700 μs represents a shift of about 1.75 periods at 2560 cps. It is necessary therefore to block one timing pulse, and to delay the next 96 pulses by 0.75 periods.

The delay flip-flop (TP-1F) is used to generate a blocking signal for the first pulse. This signal, together with the delay select signal (TP-5E), is used to gate the 180° pulses (TP-2B) which already have a delay of 0.5 periods. The delay flip-flop is set by the positive-going edge of the delay select gate, and is reset by the next positive-going edge of the P32 reference flip-flop 1.5 periods later.

The next 96 pulses are applied to the delay multivibrator (TP-3Q) where they are delayed by an adjustable amount (approximately 0.25 periods). The delayed pulses are applied to the 32-counter, which in turn drives the 5-counter until it reaches state 1 again and the delay select gate shuts off. The equipment then reverts to normal timing. In switching back to normal timing, however, an extra pulse must be added to the 32-counter to make up for the pulse dropped in going to delayed timing. If this were not done, the master station transmissions would not recur at exactly 16 cps and the remote stations would not achieve synchronism. The addition of one count in reverting to normal timing is accomplished by resetting the first flip-flop in the 32-counter from the positive-going edge of the INTEGRATE gate signal (TP-3E).

Timing pulses at 16 cps (TP-5E) also drive an additional chain of four flip-flops arranged to count by 16 and produce channel gating signals at 1 cps. These gating signals control the sequential querying of remote stations, causing them to reply in prescribed order.

(2) Modulation Circuits

The subcarrier waveform generator and modulation circuits for each channel are contained in a channel module, shown in dashed outline in the block diagram of Figure 12. Circuit boards G, H, I comprise the channel 1 module; boards J, K, and L the channel 2 module; and boards M, N, and O the channel 3 module. All circuits in the channel module are duplicated for each channel of the system Associated with each channel module is a separated but identical control unit.

A carrier flip-flop (TP-7I, 7L, 7O) in each channel module generates

the carrier waveform for that channel. The carrier flip-flop is always set for a positive output voltage at the beginning of each 1/80 sec period. Thereafter, it reverses state in response to the trigger pulses supplied from its associated carrier switch. Switch positions 1 through 16 correspond to carrier waveforms P9 througn P24 respectively. With switch positions 1, 2, and 3 used for channels 1, 2, and 3 the waveforms at (TP-7I, &L, and 70 appear as shown in Figure 15-1, 15-2, 15-3 respectively. The P32 reference carrier at TP-7P is shown in Figure 15-4 on the same time base.

The amplitude of each carrier waveform is modulated by a full-wave diode multiplier. The amplitude of the reference carrier is kept constant at +10 volts, while the amplitude of each data carrier is controlled between 0 and +10 volts by the dual potentiometer in the associated control unit. For 15/16 second, the data carrier is modulated between zero and positive full scale to represent a brightness command. For the remaining 1/16 second, the data carrier is modulated at negative full scale to represent a query signal.

The modulated carriers for each data channel (TP-5I, 5L, 5O) and the constant amplitude reference carrier (TP-5P) are summed in linear fashion by means of a resistor network (TP-8R). The photograph in Figure 15-5 shows a composite signal at this point containing the carriers P9, P10, P11 and P32. The modulation voltages are a_9 = -10V (Query), a_{10} = +10V(100% brightness) a_{11} = 0V (0% brightness), and $a_{32} = a_R$ = +10V.

Since the FM transmitter employs a phase modulator rather than a frequency modulator, the composite modulating signal cannot be applied directly but must be pre-emphasized by means of an integrator circuit (TP-2R, Figure 15-6). The rectangular composite signal is converted by this circuit into a sawtooth signal in which constant slope corresponds to constant frequency deviation of the FM carrier.

The integrated composite signal is applied directly to the deviation adjustment potentiometer in the FM transmitter, by-passing its audio stages which were found to be inadequate for this application. The relay drive signal (TP-4R) applied to the transmit-receive relays in the FM transmitter causes the r-f carrier to turn on slightly before, and to turn off slightly after, application of the modulating signal.

(3) Demodulation Circuits

Whenever a remote station is queried during a master station transmission, it should reply approximately 1/80 seconds later. The discriminator output signal (TP-7A) during the reply time for channel 1 will consist in this case of a P31 reference carrier at negative full scale amplitude, and a P9 data carrier at positive full scale amplitude. Noise which is present when no carrier is on the air, as well as undesired carrier signals, are suppressed by means of the RCV gate (TP-2D). The gated discriminator signal is applied to a push-pull amplifier (TP-4Q) which produces output signals equal in amplitude but opposite in polarity. These are applied to the full-wave diode multiplier in each channel demodulator and also to the multiplier in the reference demodulator circuits.

To demodulate the reference component of the reply signal, the P31 waveform generated locally (TP-1C) is also applied to the reference multiplier. The multiplier output signal (TP-4P) will have a negative average

voltage level during the reply time. This negative level is detected by a reset integrator circuit (TP-1P), which is held initially at zero by the INTEGRATE gate (TP-3E). The circuit is allowed to integrate during the 1/80 second RCV gate interval, and to hold its integrated voltage for the next 1/80 second interval, during which no input signal is applied.

The reset integrator waveform for the reference demodulator circuits is applied to a sample-and-hold circuit in each channel module. For the channel which was queried in the previous master station transmission, sample pulses (TP-1D) gated by the appropriate QUERY signal (TP-3G) cause the integrated reference voltage to be transferred to a sample-and-hold circuit (TP-5H). The holding time-constant of the capacitor in this circuit is long enough (10-15 seconds) to make its output voltage appear continuous, even though replies are received only for 1/80 second at a 1 cps rate.

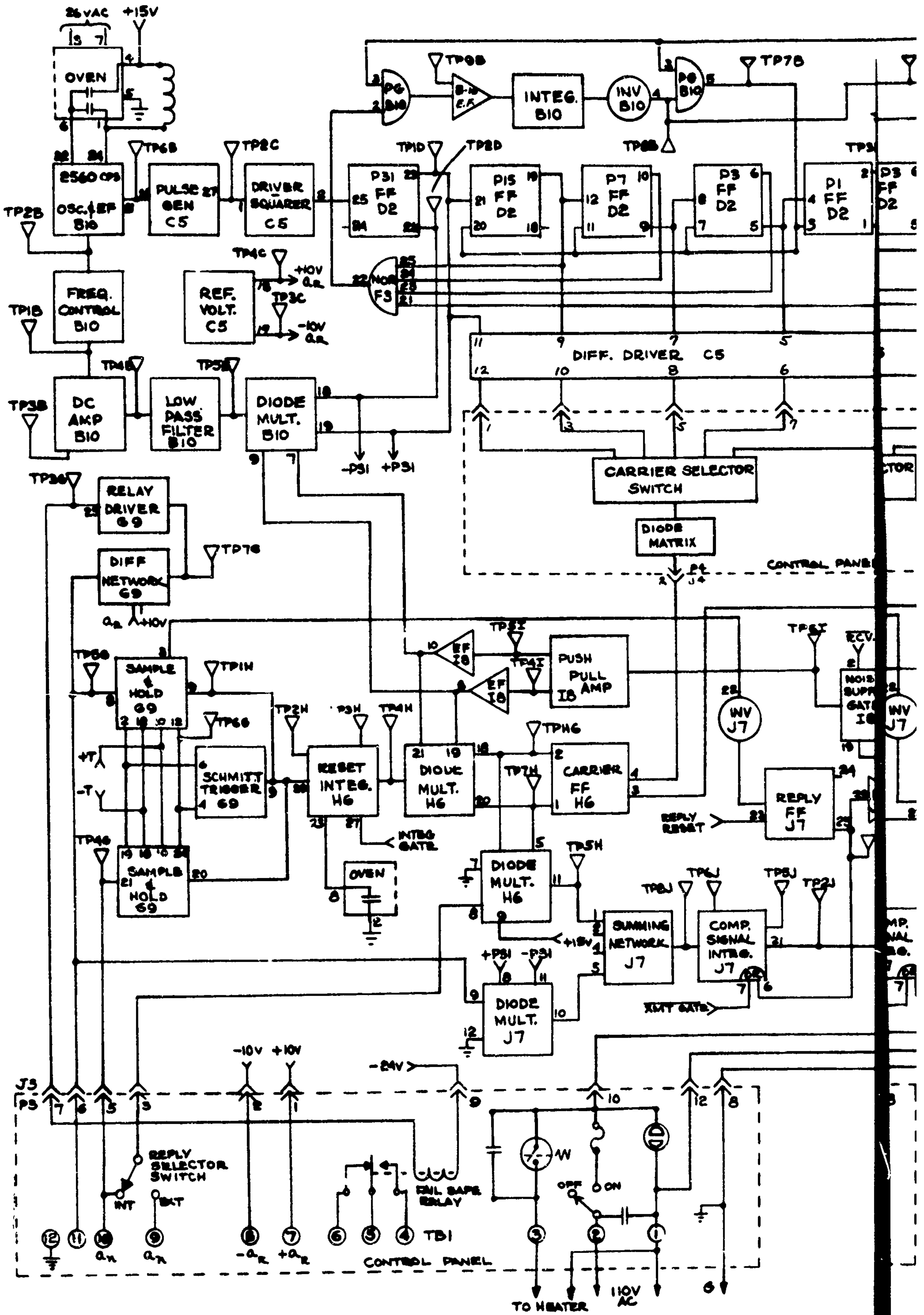
The reference voltage output (TP-5H, 5K, 5N) will be approximately -10 volts when that particular channel of the system is operating correctly. This output voltage is compared to +10 volts in a difference network (TP-7H, 7K, 7N). If the difference is large (about 5 volts or more), a relay in the associated control unit will release, causing the red indicator light to glow. If the reply reference voltage is approximately correct, the red light will extinguish, and either the yellow or green light will glow.

The data subcarrier component in the reply signal is demodulated in a similar fashion. The locally-generated carrier applied to the signal multiplier is the P9 waveform in this example. The signal multiplier output signal (TP-4I) has an average d-c voltage which can vary from 0 to +10 volts d-c. This average voltage is integrated and stored temporarily in the corresponding reset integrator (TP-1I). Sample pulses gated by the proper QUERY signal transfer the integrated voltage to a second sample-and-hold circuit for that particular channel (TP-4H).

The sampled and smoothed data reply voltage for each channel (TP-4H, 4K, 4N) is applied directly to the monitoring meter in the associated control unit. It is also compared to the command voltage by means of a difference network. If the difference voltage is within prescribed limits, the green light indicating correct response will glow. If the difference voltage is outside of prescribed limits, a second relay in the control unit will extinguish the green light and turn on the yellow light, indicating an incorrect response. A difference voltage of about ± 2 volts is required to turn on the yellow light, while a difference voltage of about ± 0.5 volts is required to restore the green light.

(C) Detailed Description - Remote Station

Figure 16 shows a detailed functional block diagram of the remote station equipment. Waveforms at significant test points of remote station are included in Figures 17 and 18. In many respects, operation of the remote station is identical with the master station.



26 VAC
+15V
OVEN
2560 CPS OSC. & EF B10
PULSE GEN C5
DRIVER SQUARER C5
P31 FF D2
P15 FF D2
P7 FF D2
P3 FF D2
P1 FF D2
PG B10
INTEG. B10
INV B10
NOR F3
FREQ. CONTROL B10
REF. VOLT. C5
DC AMP B10
LOW PASS FILTER B10
DIODE MULT. B10
-P31
+P31
DIFF. DRIVER C5
CARRIER SELECTOR SWITCH
DIODE MATRIX
CONTROL PANEL
RELAY DRIVER G9
DIFF NETWORK G9
SAMPLE & HOLD G9
SCHMITT TRIGGER G9
RESET INTEG. H6
INTEG GATE
DIODE MULT. H6
CARRIER FF H6
PUSH PULL AMP I8
EF I8
INV J7
NOISE SUPP GATE I8
REPLY FF J7
REPLY RESET
SUMMING NETWORK J7
COMP. SIGNAL INTEG. J7
XMT GATE
DIODE MULT. J7
-10V
+10V
-24V
REPLY SELECTOR SWITCH
INT
EXT
FAIL SAFE RELAY
TB1
OFF
ON
TO HEATER
110V AC

A

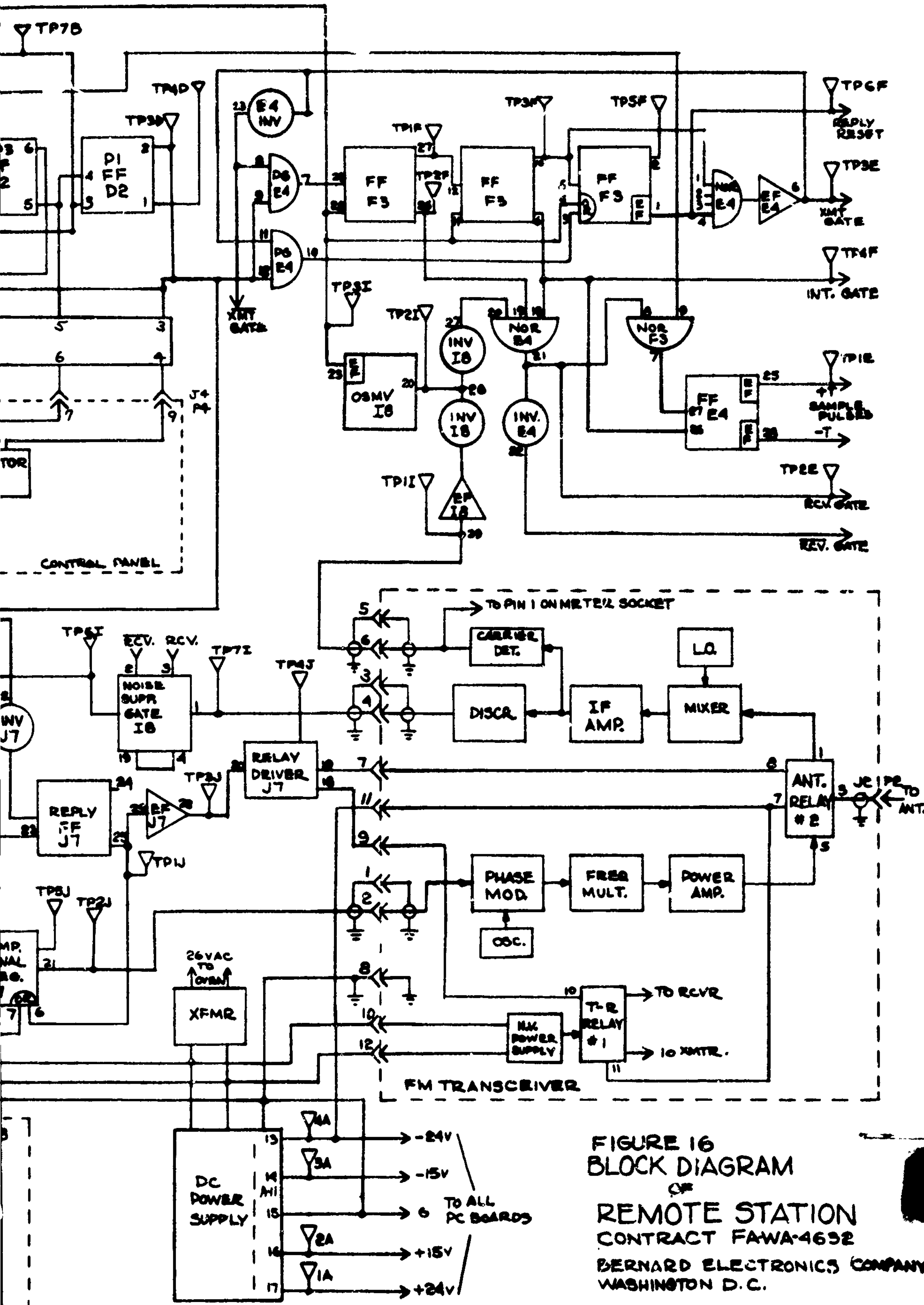
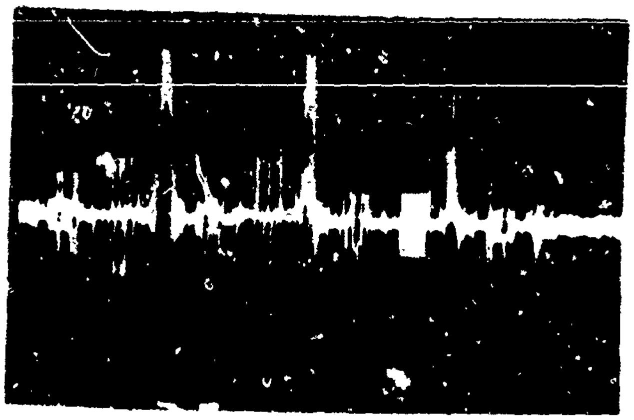
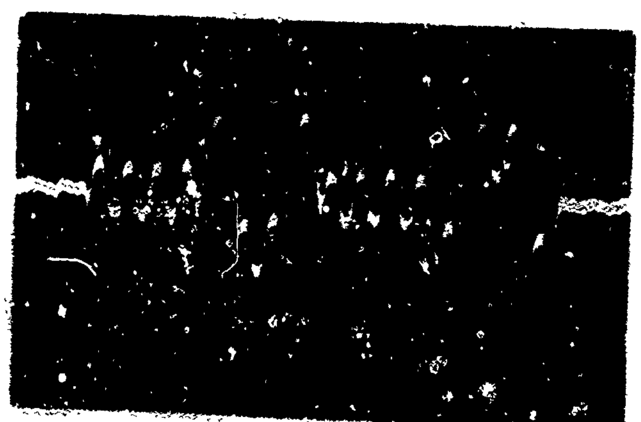


FIGURE 16
BLOCK DIAGRAM
OF
REMOTE STATION
CONTRACT FAWA-4632
BERNARD ELECTRONICS COMPANY
WASHINGTON D.C.

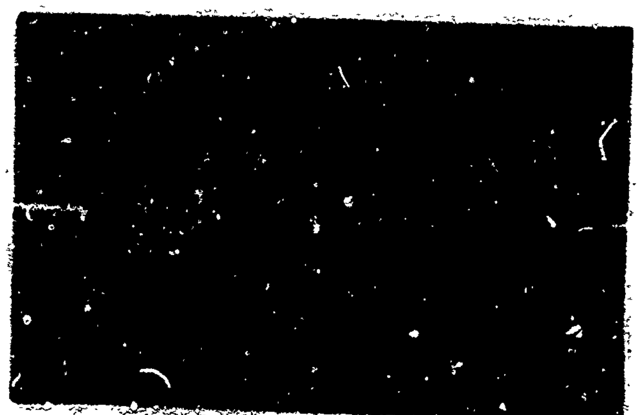


1. DISCRIMINATOR TP-7I
(INCLUDING REPLY 1, 2, 3)
(2V/CM, 10 CM = 1/4 SEC)

2. CARRIER DETECTOR TP-1I
(INCLUDING REPLY 1, 2, 3)
(10V/CM, 10 CM = 1/4 SEC)

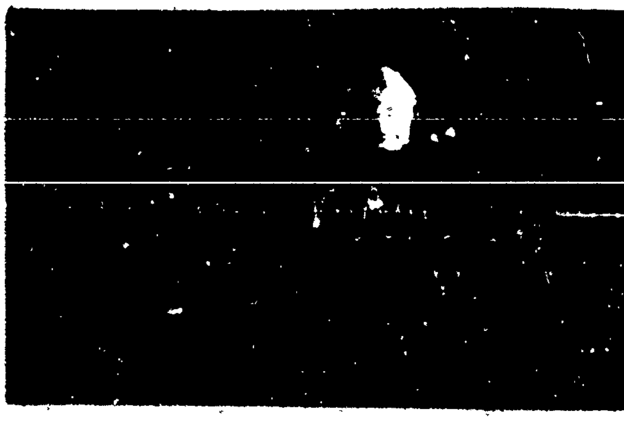


3. DISCRIMINATOR TP-7I
(CH. 1 QUERY EXPANDED)
(1V/CM, 8 CM = 1/80 SEC)



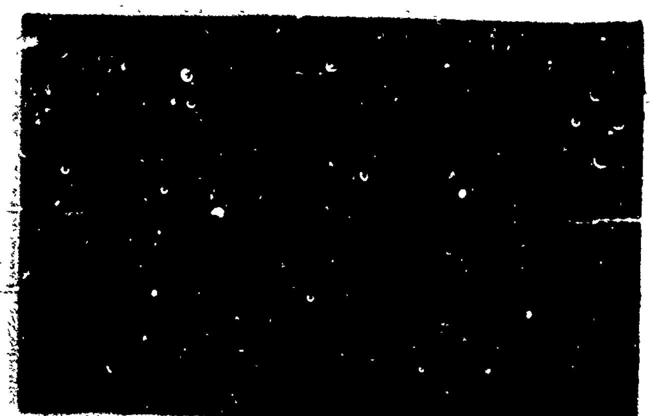
4. AFC MULTIPLIER TP-5B
(CH. 1 QUERY EXPANDED)
(10V/CM, 8 CM = 1/80 SEC)

FIGURE 17. REMOTE STATION COMMON CIRCUIT WAVEFORMS

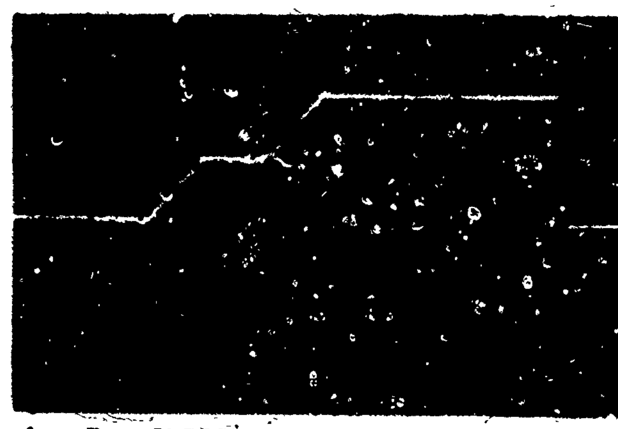


1. P_9 MULTIPLIER TP-4H
(SW. POS. 1, 8CM = 1/80 SEC)

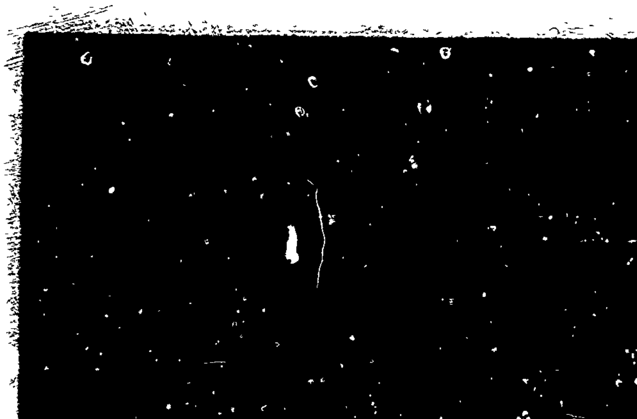
2. P_9 INTEGRATOR TP-1H
(SW. POS. 1, 4 CM = 1/80 SEC)



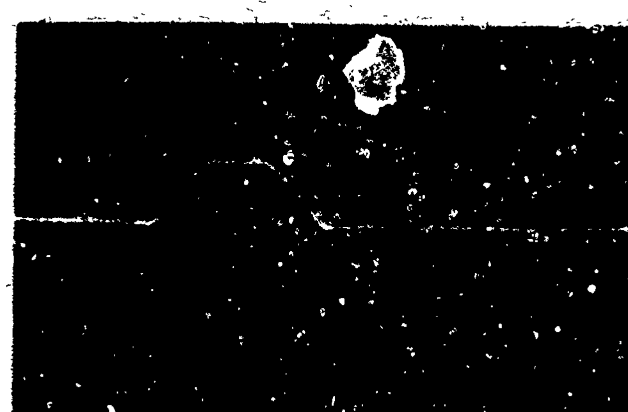
3. P_{10} MULTIPLIER TP-4H
(SW. POS. 2, 8 CM = 1/80 SEC)



4. P_{10} INTEGRATOR TP-1H
(SW. POS. 2, 4 CM = 1/80 SEC)



5. P_{11} MULTIPLIER TP-4H
(SW. POS. 3, 8 CM = 1/80 SEC)



6. P_{11} INTEGRATOR TP-1H
(SW. POS. 3, 4 CM =1/80 SEC)

(ALL WAVEFORMS 1DV/CM)

FIGURE 18. REMOTE STATION DEMODULATION WAVEFORMS

(1) Timing Circuits

The 2560 cps oscillator at the remote station employs an L-C resonant circuit. To maintain the natural oscillator frequency within a tolerance of about 0.25%, the bulk of the tuning capacitance is maintained at a constant temperature of $+75^{\circ}C$ by means of a small oven. A small amount of capacitance has been left outside the oven to compensate for temperature variations in the tuning inductance. When signals are being received from the master station, the remote station oscillator is slaved by automatic frequency control (AFC) techniques to match the frequency and phase of the received reference signal.

The output signal from the remote station oscillator (TP-6B) is a 2560 cps sine wave. At the positive-going zero crossings of the sine wave, $\emptyset^{0}$ pulse are derived (TP-2C) which trigger a chain of five flip-flops arranged to count by 32. The 1280 cps square wave produced by the first flip-flop (TP-1D) is the P31 local reference waveform for the remote station.

The five flip-flops comprising the 32-counter operate exactly the same as in the master station, except that there is no need to switch between normal and delayed timing. Only one set of trigger pulses for generating a data carrier waveform is produced; however, a rotary switch is provided for selecting any one of the 16 available combinations of trigger pulses. The 80 cps square wave produced by the last flip-flop in the 32-counter (TP-3D) is used to produce a set pulse for the carrier flip-flop (TP-7H), and also to drive the 5-counter which generates various 16 cps control signals.

The 5-counter in the remote station differs slightly from that in the master station because the 16 cps transmit control signals and receive control signals must be interchanged in time. The three flip-flops which comprise the 5-counter in the remote station are connected to cycle through the five states:

	1	2	3	4	5
TP-1F	1	0	1	0	0
TP-3F	1	0	0	1	1
TP-5F	1	0	0	0	1

State 4 (010) is detected by means of a NOR logic circuit. The next 80 cps input pulse is blocked from the input terminal of the 5-counter and used instead to reset the third flip-flop, thus producing state 5 (011).

Master station transmissions should occur when the remote station 5-counter is in state 2 (000). This state is detected by means of another NOR logic circuit to produce the remote station RCV gate (TP-2E). The carrier detector signal (TP-1I) is also connected to the input of the NOR circuit which generates the RCV gate. In this way, noise is prevented from entering the demodulation circuits when the master station is not transmitting.

The INTEGRATE gate for the remote station (TP-3F) is taken directly from the second flip-flop of the 5-counter, since it must unclamp

the reset integrator circuit during states 2 and 3. The sample pulse (TP-1E) is generated during state 3 by an additional flip-flop circuit, provided that the carrier detector signal is present and the remote station has pulled into synchronism. The sample pulse flip-flop is reset by the trailing edge of the INTEGRATE gate.

The XMT gate for the remote station (TP-3E) is generated by the same NOR circuit used to make the 5-counter re-cycle. It occurs during state 4, and is used to activate the composite signal integrator provided that the reply flip-flop (TP-1J) has been triggered.

The reply flip-flop can be triggered only if master station signals are being received (carrier detector signal present during RCV gate interval), if the remote station has pulled into synchronism (sample pulses being generated), and if a query signal (negative modulation of data carrier) is detected by the demodulation circuits. If all of these conditions exist, the reply flip-flop will operate the relays in the FM transceiver, switching it into the transmit mode. The reply flip-flop and relay drive signals start at the beginning of state 3 of the 5-counter causing the r-f carrier to turn on slightly before modulation is applied. The reply flip-flop is reset at the end of state 4 causing the r-f carrier to turn off slightly after modulation has been removed.

The discriminator output waveform in Figure 17-1 illustrates the query/reply sequence for channels 1, 2, and 3. The various remote stations always reply sequentially in the order of their assigned channel numbers (not necessarily the same as their selected carrier numbers).

The remote station oscillator and P31 flip-flop are pulled into synchronism by the AFC circuits described later. The last four flip-flops of the 32-counter and all three flip-flops of the 5-counter are pulled into synchronism by the out-of-sync detector circuits.

The out-of-sync detector contains an integrating capacitor, which when discharged, causes a positive voltage (approximately +10V) to appear at TP-8B). This positive voltage is applied to a NOR circuit at the input to the sample pulse flip-flop, thus preventing the generation of sample pulses when the remote station is out-of-sync.

Whenever signals are being received from the master station, the carrier detector signal (TP-1I, Figure 17-2) appears as a negative-going rectangular pulse. After amplification, filtering, and clipping, the carrier detector signal is applied to a one-shot multivibrator (TP-3I). The multivibrator should trigger only on the leading edge of the master station portion of the carrier detector signal (regardless of remote station replies). The duration of the multivibrator pulse is not critical; only the position of its leading edge is important.

When the multivibrator pulse occurs, the 5-counter should be in state 1 (111). If it is in some other state, it will be reset to state 1 by the leading edge of the multivibrator pulse. The last four flip-flops of the 32-counter should also be in an all 1's state when the multivibrator pulse occurs. If they are in some other state, the integrating

capacitor in the out-of-sync detector will discharge and eventually produce a positive voltage at TP-8B. This positive voltage will turn on a pulse gate (TP-7B) permitting the leading edge of the multivibrator pulse to pass through and reset the four flip-flops to their all 1's state.

If the 2560 cps oscillator and P_{31} flip-flop have been properly locked-in by the AFC circuits, the succeeding flip-flops will again be in their all 1's state when the next, and all future, multivibrator pulses occur. As long as this condition exists, the NOR circuit connected to the last four flip-flops of the 32-counter will open another pulse gate (TP-9B), permitting the leading edge of the multivibrator pulse to pass through and charge the integrating capacitor. The d-c level at TP-8B will then go to a negative voltage (approximately -15V) and allow sampling pulses to be generated.

Should the AFC circuits not be locked, the integrating capacitor in the out-of-sync detector will alternately charge and discharge at a rate determined by the frequency error of the oscillator. The charging time constant is sufficiently slow that 4-5 sequential multibrator pulses must occur at the proper time relative to the counter flip-flops before the level at TP-8B exceeds the in-sync threshold (approximately -5 volts). The discharge time constant is also sufficiently slow, that an occasional dropped multivibrator pulse will not cause lose of synchronism, nor will an occasional spurious multivibrator pulse reset the counters falsely.

(2) Demodulation Circuits

The discriminator output signal from the FM receiver (TP-7I) during a master station transmission is shown expanded in Figure 17-3. It is a limited-bandpass reproduction of the composite modulation signal generated at the master station. As before, the example shown is for channel modulations;

a_9 = -10V (Query)

a_{10} = +10V (100% modulation)

a_{11} = 0V (0% modulation)

a_{32} = +10V (reference)

Noise in the discriminator signal when no carrier is present, as well as the remote station replies, are suppressed by means of the remote station RCV gate (TP-2E). The RCV gate is held to approximately the correct timing by the out-of-sync detector circuit already described, even though the AFC circuits may not have achieved lock. After gating, the discriminator signal is applied to a push-pull amplifier (TP-4I), as in the master station. The equal but opposite output signals from the push-pull amplifier are applied to a full-wave diode multiplier in the AFC loop, and to an identical multiplier in the signal demodulation circuits.

In the AFC multiplier, the received composite signal is multiplied by the locally generated P_{31} waveform (TP-1D). When the local P_{31} waveform has the proper frequency and phase relative to the received composite signal, the multiplier output waveform (TP-5B, Figure 17-4) appears as a series of "S" curves having a zero average voltage. If the local P_{31}

square wave should be slightly delayed in phase (frequency too low), the "S" curves become more rounded on top, producing a positive average voltage. If the local P31 square wave should be slightly advanced in phase (frequency too high), the "S" curves become more rounded on the bottom, producing a negative average voltage. Only the P32 reference component of the received composite signal affects the average voltage in the AFC multiplier. The other carrier components when multiplied by P31, always produce an average voltage of zero, even in the presence of a timing error.

The average voltage produced by the AFC multiplier is extracted by means of a low-pass filter (TP-4B). A double time-constant filter is used to achievd a proportional-plus-integral type of control in the AFC loop. After d-c amplification (TP-1B), the filtered AFC voltage is applied as a control signal to the 2560 cps oscillator. The polarity of the control signal applied is such as to pull the oscillator frequency in the direction which will correct any timing error in the local P31 waveform and produce a zero average voltage in the AFC multiplier. The pull-in range of the oscillator is approximately 10 cps on either side of 2560 cps. Near the limitssof the pull-in range, a static phase error can still exist. For this reason, the natural oscillator frequency should be maintained as close to 2560 cps as possible.

The demodulation of data signals operates in a similar way as in the master station. The received composite signal is multiplied by the carrier waveform (P9 through P24) generated locally at the remote station (TP-7H). The multiplier output signals (TP-4H) when P9, P10, or P11 is selected are shown in Figures 18-1, 18-3 and 18-5 respectively. The corresponding reset integrator waveforms (TP-1H) are shown in Figures 18-2, 18-4, and 18-6. The P9 integrator charges to -10V in this case, indicating a query. The P10 integrator charges to +10V, and the P11 integrator to 0V, corresponding to the modulations applied at the master station.

When the integrated voltage is more negative than about -5 volts (as in Figure 18-2), the Schmitt trigger circuit (TP-6G) reverses state, causing sampling pulses to transfer the peak negative voltage to the reference data holding circuit (TP-5G) and to trigger the reply flip-flop (TP-1J). When the integrated voltage is zero or positive (as in Figure 18-4 or 18-6), the Schmitt trigger does not operate. Sampling pulses then transfer the integrated voltage to a command data holding circuit (TP-4G).

The sampled and stored reference voltage (approximately -10 volts d-c) and command data voltage (0 to +10 volts d-c) are brought out as external signals from the remote station. The stored reference voltage is also compared to a local +10 volt d-c supply by means of a difference network (TP-7G). If the difference is more than about 5 volts, the fail-safe relay on the control panel will de-energize, indicating a system failure.

(3) Modulation Circuits

The reply transmission from the remote station consists of a data carrier modulated between 0 and +10 volts (TP-5H), and a P31 reference carrier modulated at -10 volts. Modulation of the data carrier is controlled either internally by the demodulated data command (TP-4G), or externally (TB1-9) from a device such as a servomechanism which responds to the data command. Modulation of the reference is always controlled internally by the demodulated reference voltage from the master station. These portions of the remote station operate almost identically with those at the master station.

One exception is that half-wave rather than full-wave multipliers are used in the remote station. This simplification is possible because the modulation voltages change very slowly (no command/query switching). One of the signal input terminals can be grounded, because after a-c coupling of the multiplier output signal, its peak-to-peak amplitude will still vary in the desired manner.

(D) Detailed Description - Special Circuits

Complete schematic diagrams of all circuits in the Wireless Control System are included in the Maintenance Instructions submitted as a separated document. Most of the circuits are conventional and should not require further explanation here. A few circuits are unique, and were developed specifically for this equipment as described below.

(1) Diode Multiplier

A schematic diagram of the diode multiplier circuit is shownin Figure 19. The basic multiplier circuit composed of transistors Q_1 and Q_2 is used both for modulation and demodulation. In the modulation circuits only, transistor Q_3 is added for command/query switching.

The basic multiplier circuit operates very much like two AND gates followed by an OR gate, except that one input signal to each AND gate is a continuously variable voltage. For modulation, the variable inputs are $+a_n$ (0 to +10V) and $-a_n$ (0 to -10V). The base voltage of Q_1 goes to the $+a_n$ level if P_n = +15V (normalized +1 level), but is clamped to +15V if P_n = -15V (normalized -1 level). Similarly, the base of Q_2 goes to the $-a_n$ level if P_n = -15V, but is clamped to +15V if P_n = +15V. The common emitter of Q_1 and Q_2 goes to the more negative of the two base voltages, which is $+a_n$ if P_n = +15V or $-a_n$ if P_n = -15V. The output signal has the same waveshape as P_n, but its peak-to-peak amplitude varies from 20 volts down to zero as a_n varies from +10 volts to zero.

During query modulation, transistors Q_1 and Q_2 are cutoff by clamping their bases to +15 Volts. Transistor Q_3, which was held cutoff in a similar way during command modulation, is unclamped during query modulation. The signal appearing at the common emitter terminal is $-P_n$ under these conditions. The amplitude of the inverted P_n carrier is held

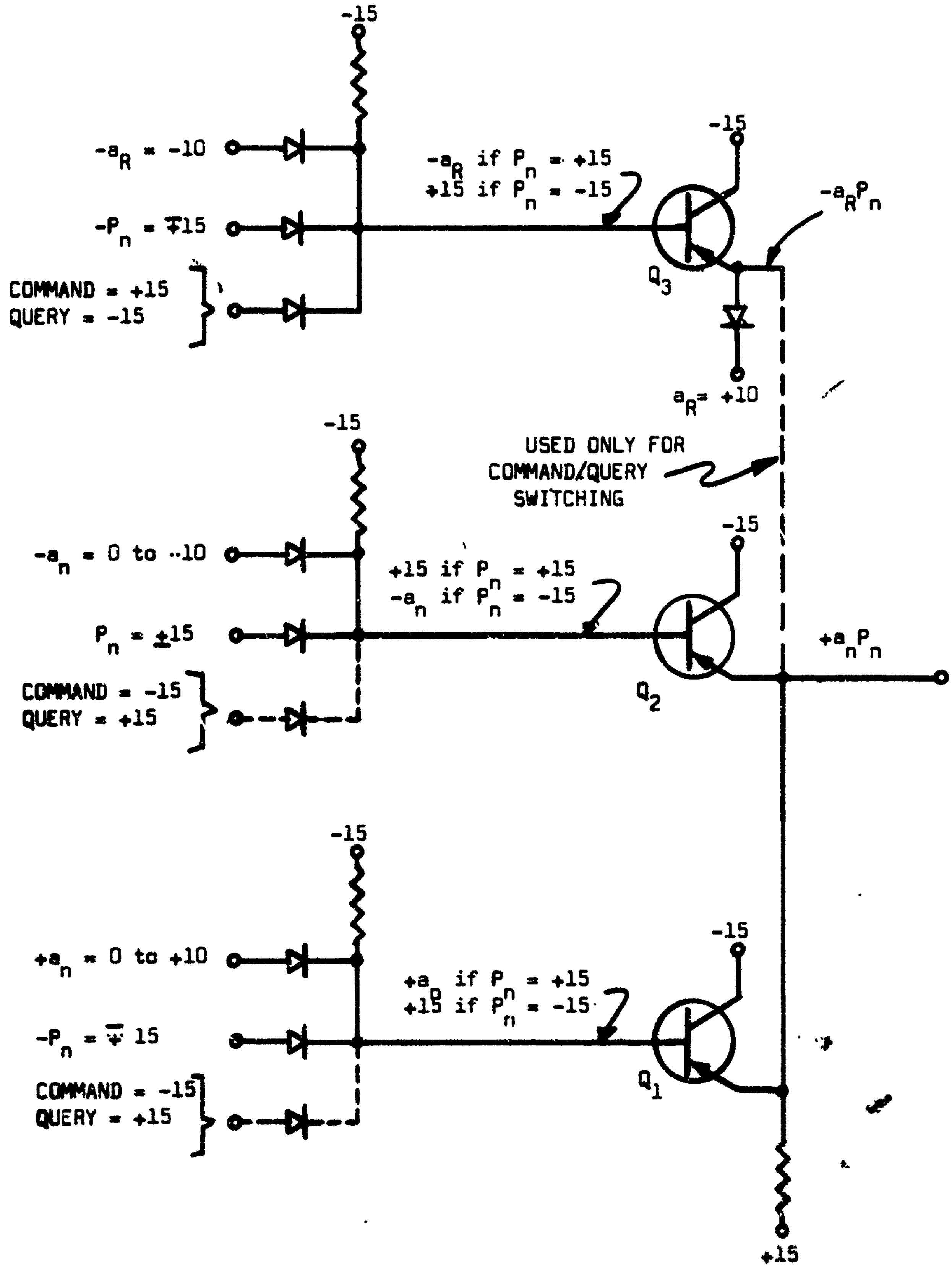


FIGURE 19. DIODE MULTIPLIER

to ± 10 volts by clipping diodes.

(2) Reset Integrator

Figure 20 shows a simplified schematic diagram of the reset integrator used both for demodulation and for pre-emphasis of the composite modulating signal.

The capacitor C is initially clamped at ground potential by the reset transistor Q_1. When Q_1 is cutoff by the INTEGRATE gate signal, capacitor C charges through resistors R_1 and R_3 towards the input voltage e_x. Resistor R_1 is made variable as a means of controlling the rate of charging, or slope. The capacitor voltage is amplified by means of a stabilized d-c amplifier whose gain is set at approximately 10 by negative feedback. The amplifier is adjusted to give zero volts output for zero volts input.

To eliminate the usual exponential curvature of an R-C integrator, the in-phase output of the d-c amplifier is fed back to the junction of R_1 and R_3 through the linearity adjustment resistor R_2. If the capacitor voltage is e_c and the amplifier input resistance is R_4, the capacitor charging current is:

$$i_c = \frac{1}{R_1}\left[e_x + \frac{10R_3}{R_2} e_c - e_c\right] - \frac{e_c}{R_4} \tag{5}$$

where $R_1, R_2 \gg R_3$

If the linearity control R_2 is properly adjusted, the charging current can be made exactly proportional to the input voltage e_x; that is:

$$i_c = \frac{e_x}{R_1} \quad \text{and} \quad e_c = \frac{1}{R_1 C}\int e_x dt$$

$$\text{if } R_2 = \frac{10R_3 (R_1 + R_4)}{R_1 R_4} \tag{6}$$

Since the output signal from the amplifier is $10e_c$, the circuit provides gain as well as linear integration.

(3) Sample-and-Hold Circuit

The sample-and-hold circuit shown in Figure 21 is used in demodulation to store the final voltage of each reset integrator and to present this voltage as a continuous d-c output signal at low impedance.

The reset integrator waveform is connected through emitter followers Q_1 and Q_2, to the bases of charging transistors Q_3 and Q_4 respectively. During the sampling interval (1/80 second), capacitor C is charged either positively through Q_4 or negatively through Q_3 to the voltage of the

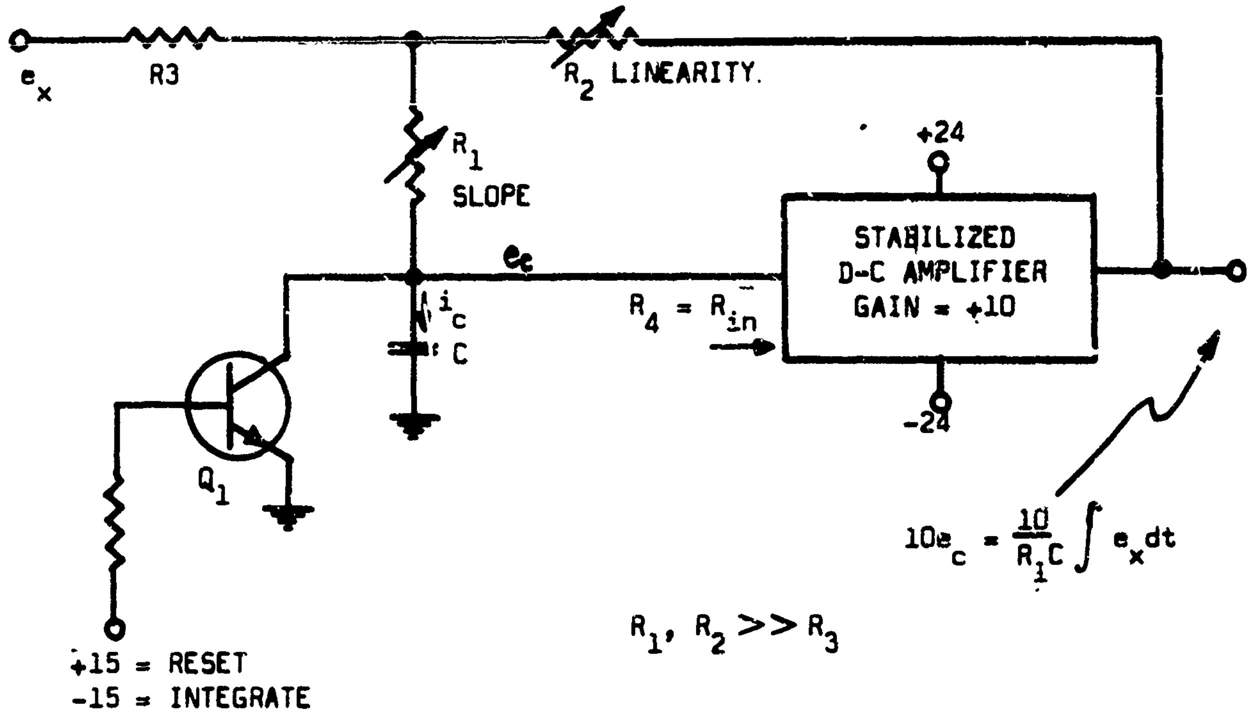


FIGURE 20. RESET INTEGRATOR

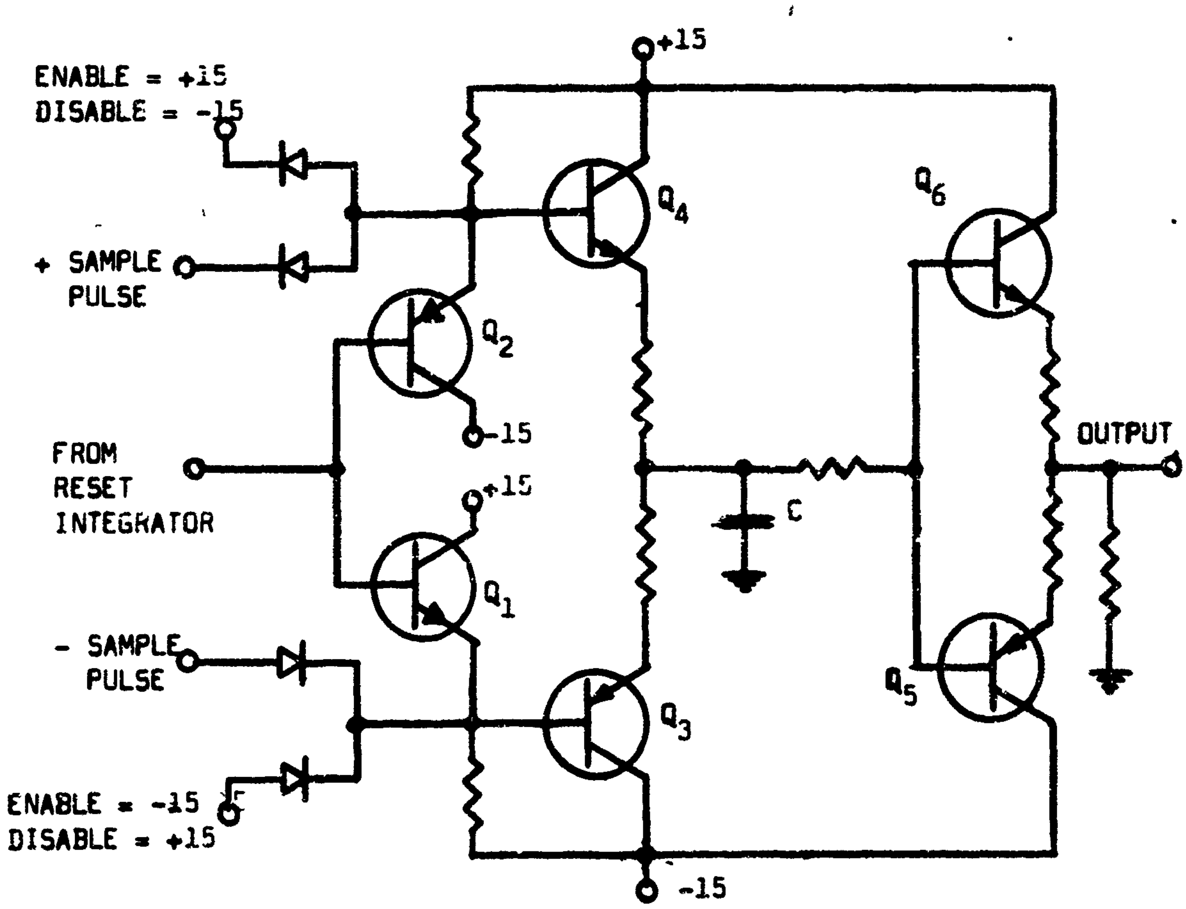


FIGURE 21. SAMPLE-AND-HOLD CIRCUIT

of the integrator. Small resistors in the emitter circuit of Q_3 and Q_4 limit the charging current to about 100 ma. Emitter followers Q_1 and Q_2 prevent the charging current from causing any significant change in the integrator voltage.

At the end of the sampling interval, the charging transistors are cutoff by removal of the $\pm$ sampling pulses. The - sampling pulse signal reverts to its resting level of +15 volts, and clamps the base of Q_3 to the same level. The base of Q_4 is clamped to -15 volts by the resting level of the + sampling pulse. Additional clamping diodes are provided at the bases of Q_3 and Q_4 to permit selective sampling. In the remote station, these additional diodes are controlled by the Schmitt trigger circuit to store command and query voltages separately. In the master station, they are controlled by the query gating signals to select reply voltages only from a particular remote station.

Between sampling intervals, capacitor C holds the last stored voltage. The value of C is 100 μf, and the holding time constant is about 10 seconds. The output stage composed of Q_5 and Q_6 is a complementary emitter follower having an input impedance of approximately 100 K and an output impedance of approximately 500 ohms for both positive and negative voltages.

(4) Temperature Compensation Circuits

During temperature testing of the equipment, it was found that the zero and full scale calibration of the various channels varied as much as 2 volts out of 10 under extreme temperature conditions. It was also found that the remote station oscillators would drop out of synchronism at extreme temperatures unless compensation circuits were provided.

. In the modulation circuits, gain of the master station composite signal had to be decreased slightly with increasing temperature to maintain system calibration. This effect was achieved by connecting a thermistor network from the summing junction to ground.

In the remote stations only, the natural frequency of the timing oscillators was stabilized by using a small oven to maintain the tuning capacitors at +75°C. In addition, the AFC multiplier exhibited a zero offset which varied with temperature, tending to pull the natural frequency away from 2560 cps. The latter effect was compensated by a thermistor network at the input to the multiplier.

A similar thermistor network was connected at the input to each signal demodulation multiplier, to maintain the zero signal level independent of temperature. In the remote stations only, the reset integrator capacitor was placed in the same +75°C oven for the oscillator. Overall gain compensation of the demodulator circuits was obtained by a thermistor network at the input to the common push-pull amplifier.

The compensation networks were designed by substituting a calibrated variable resistance in place of each network and recording the values required for correct operation at $-10^{\circ}C$, $+25^{\circ}C$, and $+55^{\circ}C$. In every case, a resistance which decreased with increasing temperature was needed. The resistance variation required in most cases was obtainable with a thermistor R_T which decreases exponentially with temperature ($-4.4\%/{}^{\circ}C$), having a fixed resistor R_1 in parallel and another fixed resistor R_2 in series. The design equations are:

$$R_T = \frac{1.11\Delta_1\Delta_2(\Delta_1+\Delta_2)}{(\Delta_1-0.352\Delta_2)^2} \tag{7}$$

$$R_1 = \frac{5.56R_T(\Delta_1-0.352\Delta_2)}{6.58\Delta_2-\Delta_1} \tag{8}$$

$$R_2 = R_o - \frac{R_T R_1}{R_T+R_1} \tag{9}$$

Where R_o = desired resistance at $+25^{\circ}C$

Δ_1 = desired resistance increase at $-10^{\circ}C$

Δ_2 = desired resistance decrease at $+55^{\circ}C$

An exact 3- point fit to the desired resistance curve is obtainable, provided that $0.325 \leq \Delta_1/\Delta_2 \leq 6.58$. In a few cases, no change or even a slight increase in resistance was needed at $+55^{\circ}C$. This type of curve was fitted approximately by connecting a positive temperature coefficient Sensistor across the series resistor R_2. The best fit was obtained by trial and error.

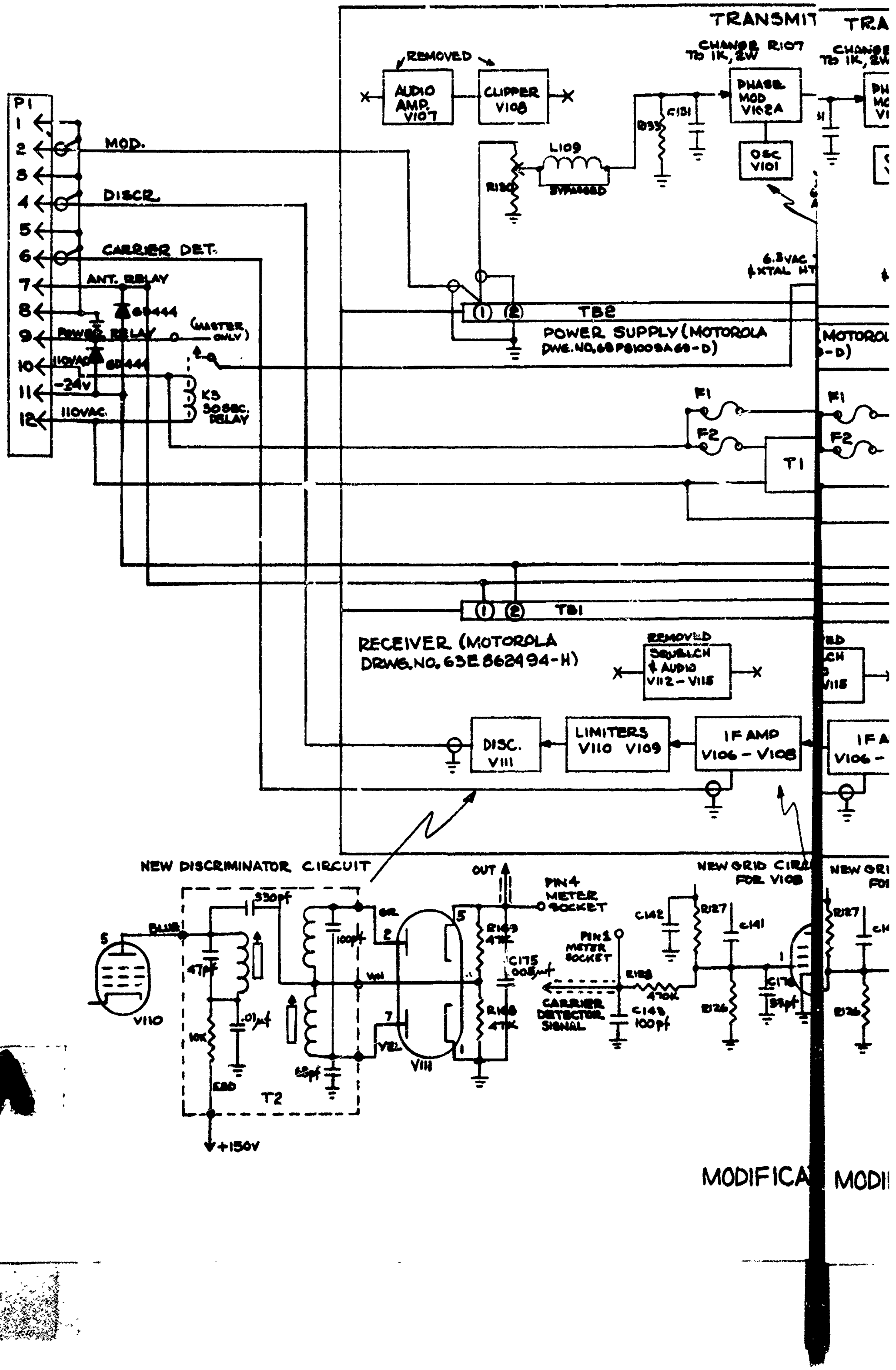
(5) Transceiver Modifications

Figure 22 shows all of the circuit modifications made in the Motorola L43GGB-1100A taansceivers. The modifications include the removal of audio input-output stages, replacement of transmit-receive relays, provision for a carrier detector output signal, redesign of the discriminator, and stabilization of power supplies.

DISCUSSION OF POSSIBLE IMPROVEMENTS

As indicated by the test results in Appendix A, the experimental model of the Wireless Control System performed quite satisfactorily with respect to system range, bandwidth, crosstalk, accuracy, linearity, and failsafeness. One aspect of its performance which does need improvement is its stability under extreme temperature conditions.

In future models, it is quite feasible to eliminate the temperature problem and also to make the equipment smaller, lighter, and easier to use. The ultimate cost of the equipment, when engineered for quantity production, should be very attractive.



TRANSMIT
REMOVED
AUDIO AMP. V107
CLIPPER V108
CHANGE R107 TO 1K, 2W
PHASE MOD V102A
OSC V101
L109
BYPASSED
R130
P1
MOD.
DISCR.
CARRIER DET.
ANT. RELAY
POWER RELAY
(MASTER ONLY)
110VAC
-24V
110VAC
K3 30 SEC. RELAY
6.3VAC & XTAL HT
TB2
POWER SUPPLY (MOTOROLA DWG. NO. 68P81009A60-D)
F1
F2
T1
TB1
RECEIVER (MOTOROLA DRWG. NO. 63E862494-H)
REMOVED
SQUELCH & AUDIO V112 - V115
DISC. V111
LIMITERS V110 V109
IF AMP V106 - V108
NEW DISCRIMINATOR CIRCUIT
NEW GRID CIRCUIT FOR V108
OUT
PIN 4 METER SOCKET
PIN 1 METER SOCKET
CARRIER DETECTOR SIGNAL
V110
V111
T2
+150V
MODIFICA

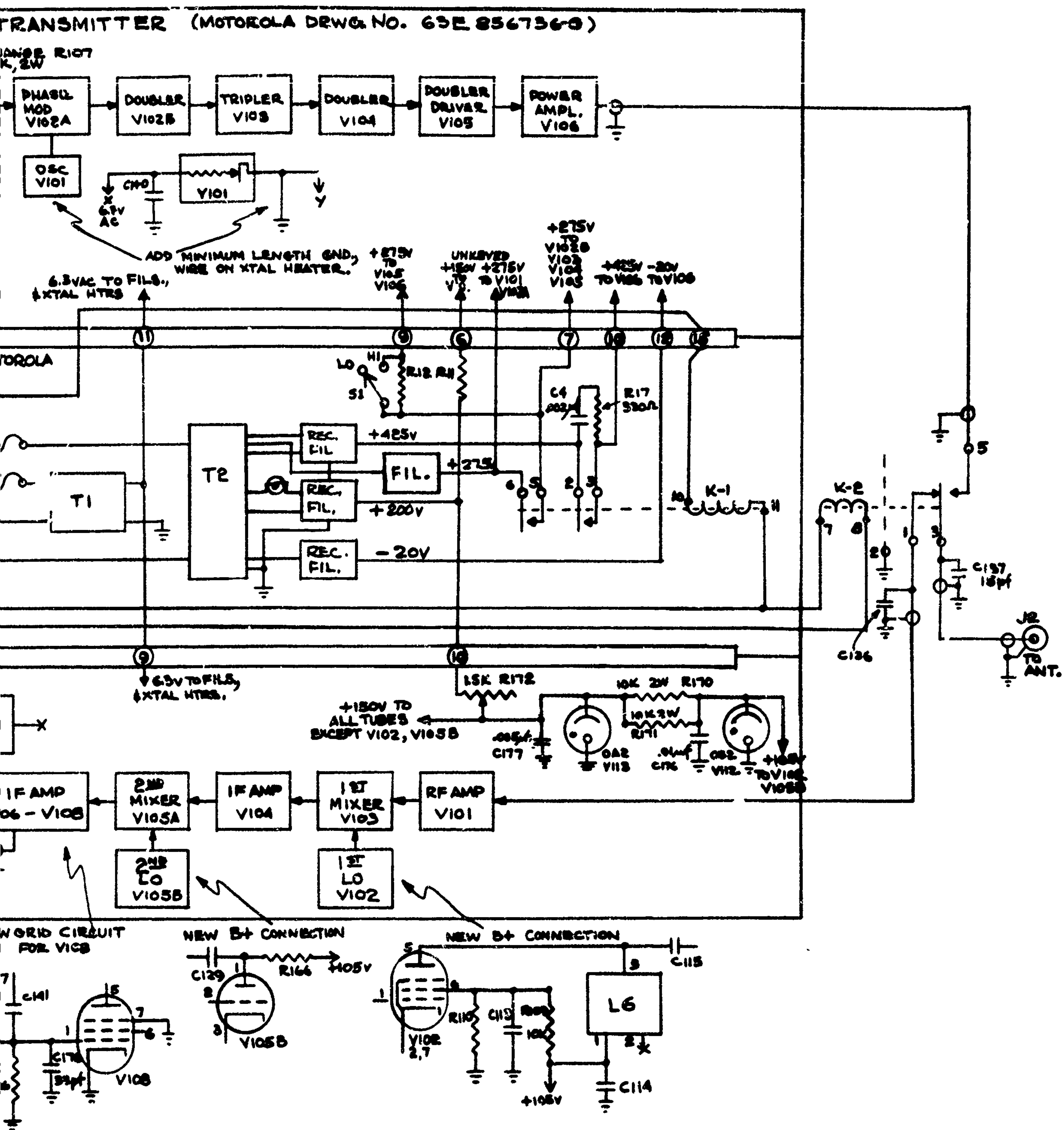


FIGURE 22.
MODIFICATIONS TO
FM TRANSCEIVER

ODIFICATIONS TO FM TRANSCEIVER

(A) Components and Circuits

One of the circuits which should be improved in future models is the remote station oscillator. The natural frequency of this oscillator must be inherently stable, and yet be capable of control by an AFC voltage. In place of the oven-stabilized L-C circuit now used, oscillators employing tuning fork or crystal stabilization should be investigated.

The majority of temperature problems encountered could be eliminated by using silicon transistors and diodes exclusively. Such semi-conductor components are now appearing on the market which are very competitive with germanium units in price. In particular, silicon PNP transistors which were formerly much more expensive than the NPN type are now becoming available at reasonable cost.

Variations in system gain with temperature could be eliminated through the use of amplifier circuits having higher open-loop gain and greater amounts of negative feedback. Similar techniqees could be used to eliminate the temperature-variable d-c offset voltages which were encountered in the multiplier, reset integrator, and sample-and-hold circuits.

System size, weight, and power drain could be significantly reduced if transistorized r-f equipment were used. The present warmup time of 1-2 hours could also be significantly reduced. Depending upon the results of FAA evaluation tests, it may be possible to reduce the r-f power output below 10 watts.

With these improvements, it is believed that the original temperature specification of -55°C to $+55^{\circ}$C can be met. The present equipment size, weight, and power drain could probably be reduced by at least one third.

Another area for possible improvement is in the control units at the master station. It is questionable, for example, whether the use of reply meters, which are relatively fragile and expensive, is really justified for future models. The information most needed by a control operator is contained in the command lever setting and the red/yellow/green status lamps. The control units can also be simplified by eliminating the gearing currently used to adapt the 360° potentiometers to the 75° meters. Sector potentiometers can be used if necessary. With these improvements, it should be possible to meet or surpass the original size limitation of 4" x 6" panel space per channel. A common dimming control for all channels would also be an improvement.

(B) Alternate Simplified Systems

The Wireless Control System in its present form is probably more complex than it needs to be for general use. Much of the complexity arises from the inclusion of the reply path and its associated problems of transmit-receive switching on a single r-f frequency. Reply signal monitoring does appear desirable from an operational standpoint; however, its value must be weighed against the system cost and complexity which it introduces.

Future systems might be designed with the idea of using 1-way control to achieve a basic, low cost system. The basic master station equipment would transmit only, and the basic remote stations would receive only. In a system of this type, the master station could transmit continuously (except when in standby), thereby eliminating all problems of transmit-receive switching. The 5-counter and 16-counter circuits could probably be eliminated, and single potentiometers and half-wave multipliers could be used for modulation. At the remote stations, the r-f transmitters would not be needed, nor would the 5-counter and its associated control circuits. The reset integrators and sample-and-hold circuits could probably be replaced with simplified d-c amplifiers and low pass filters.

Reply signal monitoring, where desired, could be included as an add-on feature. Maximum system performance and flexibility would be achieved if a 2nd r-f frequency were provided for the time-shared reply signals.

Another possibility for greater system flexibility is to provide for more than one channel per remote station. The amount of additional equipment required at the remote station would be something like 10% per channel. The additional channels could be used not only for lighting control, but for various other switching or proportional control functions as well.

Since the multiplex modulation/demodulation portions of the present system are essentially independent of the r-f link, system economy might also be enhanced by sending the composite signal over existing power cables. The problems of by-passing the control signals around various power devices, or adapting them to multiple power sources would have to be investigated.

(C) Production Cost Estimates

The figures given below represent a best current estimate of production costs for a Wireless Control System of the type developed under this contract. These estimates assume a completed and approved prototype design of good commercial quality. The figures given represent cost per channel (either 2-way or 1-way). A production run of at least ten 16-channel systems has been assumed.

The three categories of equipment shown represent (1) remote station equipment all of which is associated with a particular channel, (2) master station equipment which must be duplicated for each channel, and (3) master station common equipment which can be pro-rated by 1/16 for each channel.

PRODUCTION COST ESTIMATE FOR 16-CHANNEL SYSTEM

	2-way	1-way
1. Remote Station		
R-F equipment	450	250
ORTHOMUX equipment	500	200
Power Supply	200	100
Case and Hardware	250	150
Assembly and Test	150	100
	$1,550	$800
2. Master Station Channel Equipment		
Control unit	150	100
ORTHOMUX equipment	200	100
	$350	$200
3. Master Station Common Equipment		
R-F equipment	450	250
Timing and control circuits	250	100
Power Supply	250	125
Case and Hardware	250	125
Assembly and Test	400	200
	$1,600/16	$800/16
Total Cost per Channel	$2,000	$1,050

CONCLUSIONS

1. The experimental model of the Wireless Control System has demonstrated that the basic design approach is valid.

2. System objectives have been met with respect to range, bandwidth, crosstalk, accuracy, linearity, and failsafeness.

3. Temperature stability of the system needs improvement; however this problem is not basic and can be eliminated through redesign of critical circuits and the use of silicon transistors only.

4. Expansion to 16 or more channels appears entirely feasible.

5. The use of standard, continuous 0-10 volt d-c signals makes the system usable for numerous applications other than lighting control; however special interface equipment at the remote stations will be needed for each application.

6. In its present form, the system is probably over-complex for general use. Much of the complexity is accounted for by the inclusion of time-shared ~~reply signals and the associated problems of transmit-receive switching~~.

7. The vacuum tube r-f equipment accounts for a large part of the system size, weight and power drain; as well as the needed warmup time of 1-2 hours.

8. The estimated production cost of $2,000 per 2-way channel appears attractive, and can be reduced to roughly half that amount for simpler types of control.

RECOMMENDATIONS

1. It is recommended that the design of the experimental Wireless Control System be improved in the following respects:

- (a) Improved temperature stability.
- (b) Use of transistorized r-f equipment.
- (c) Use of 1-way control only to achieve a simplified, low-cost, basic system.
- (d) Provision for reply signal monitoring as an add-on feature, preferably using a 2nd r-f frequency to ease the problems of transmit-receive switching.
- (e) Improved design of control units for simplified operation, possibly eliminating the reply meters.
- (f) Expansion of the system to 16 or more channels.
- (g) Provision for more than one channel per remote station.

2. A study and development program covering appropriate interface equipments at the remote stations is also recommended.

3. To enhance the flexibility and economy of the system, it is recommended that an investigation be made of the possibilities of sending the composite command and reply carrier signals over existing lighting power circuits, bridging power apparatus as necessary.

4. It is further recommended that studies be undertaken to determine how the Wireless Control System can be adapted for other airport uses than lighting control.

WIRELESS CONTROL SYSTEM

FOR AIRPORT LIGHTING

CONTRACT FA-WA-4632

ACCEPTANCE TEST PROCEDURE

1. General Workmanship

Inspect the components, wiring, and mechanical assembly of each equipment to verify that the workmanship meets the standards of good commercial practice.

2. Locking Provisions

Inspect each remote station equipment to verify that it is equipped with adequate tamperproof locking provisions.

3. Primary Power Consumption

The equipment alignment procedures should be completed before making this test. Connect the antenna jack of the master station and each remote station equipment to a 4-arm, 50-ohm attenuator as in Figure A-1, inserting 30 db attenuation in each arm. Measure the current drawn by each equipment from the nominal 115 volt, 60 cps primary power source. Verify that the average power consumption is not more than 500 watts for the master station, nor more than 200 watts for each remote station.

4. Panel Dimming Provisions

Verify that the panel illumination for each control unit of the master station can be varied from full bright to full off by means of the panel knob provided.

5. Control Provisions

Verify that ON-OFF, 5-step, and continuous control are provided for each of the three control channels of the system. The five detented steps should occur at 20%, 40%, 60%, 80%, and 100% of full scale. Continuous control should be possible everywhere except in the immediate vicinity of each detented step.

6. Failsafe Provisions

6.1 Remote Station Failure

With the system fully adjusted and each remote station set for internal reply, verify that the green light on each control panel is lit, and that the failsafe relay in each remote station is energized (TB 1-5 to TB 1-6 open, and TB 1-5 to TB 1-4 closed). Turn off the power switch at each remote station in turn, and verify that the corresponding green light turns off, the corresponding red light turns on, and corresponding remote failsafe relay de-energizes. Measure the time elapsed before the master station red light turns on.

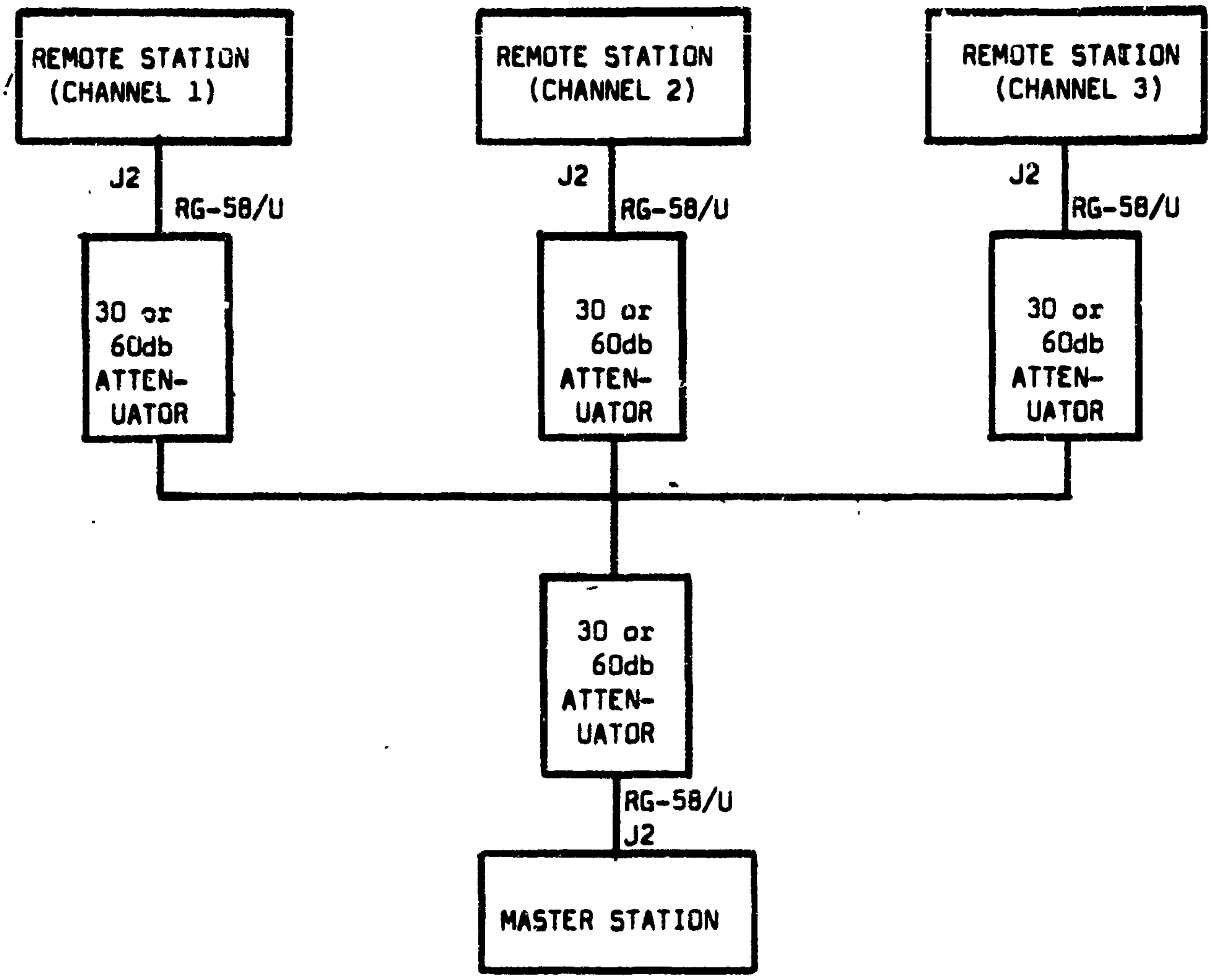


FIGURE A-1. RF DISTRIBUTION FOR TESTING

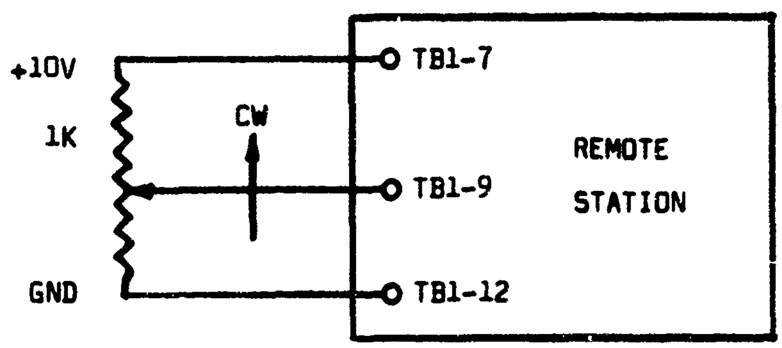


FIGURE A-2. SIMULATED EXTERNAL REPLY

6.2 Master Station Failure

Turn on power at all remote stations, and turn off power at the master station. Verify that all lights extinguish at the master station and that all remote failsafe relays de-energize. Measure the time elapsed before each remote station relay drops out.

6.3 Incorrect Reply

Turn on power to all equipments. At each remote stations, set the reply selector to EXTERNAL and simulate an external reply signal as shown in Figure A-2. Verify that the green light turns off and the yellow light turns on for each channel under the following conditions:

Reply Meter Indication	Brightness Control Knob
100	80
80	100 or 60
60	80 or 40
40	60 or 20
20	40 or 00
00	20

Return the reply selector switch in each remote station to INTERNAL.

7. Operation Time

Verify that the panel meter and remote station output voltage (TB 1-10) for each channel respond within 1 second to changes in the control setting knobs.

8. Channel Accuracy

Set the carrier selector switches in Channels 1, 2, and 3 (master and remote stations) to positions 1, 2, and 3 respectively. Set all brightness control knobs at 80. Taking each channel in turn, set its brightness control knob to 0, 20, 40, 60, 80, and 100. Verify that the corresponding meter indication at the master station and the d-c voltage at TB 1-10 of the corresponding remote station agree with the control knob setting within ±2% of full scale.

9. Channel Crosstalk

Set all brightness control knobs at 80. Change the carrier selector switches (master and remote stations) as indicated below. For each combination of carrier, vary the channel 1 control knob from 0 to 100 and measure the change in the channel 2 and 3 meters. Similarly vary the channel 2 and channel 3 knobs from 0 to 100% and measure the change in the other two meters.

(It may be necessary to readjust the zero, slope, and linearity of the reset integrators after switching the carriers.)

Channel 1 Carrier	Channel 2 Carrier	Channel 3 Carrier
1	2	3 to 16
3	4	5 to 16
5	6	7 to 16
7	8	9 to 16
9	10	11 to 16
11	12	13 to 16
13	14	15 to 16
14	15	16

10. System Range

An attenuation of 120 db between stations simulates the maximum system range of 3 miles, while an attenuation of 60 db simulates the expected minimum range of 0.5 miles. Verify that when 60 db attenuation is placed in each arm of the attenuator of Figure A-1, no more than 2% change occurs in the panel meter readings.

11. R-F Spectrum

The requirements on carrier stability and spurious emission supression are covered by the FCC certification of the Motorola L43GGB-1100A transceiver equipment. If the peak FM deviation does not exceed 5 kc, an emission bandwidth can be assured. Measure the peak FM deviation as described in the equipment alignment procedure and verify that the deviation does not exceed 5 kc.

12. Interference Rejection

The requirements on interference rejection are covered by the FCC certification of the Motorola L43GGB-1100A transceiver equipment.

13. Temperature Test - Master Station

Remove the control panel assembly from the master station equipment. Using extension cables for the control panel assembly, primary power, and r-f signal, place the remainder of the master station equipment in a controlled temperature chamber. Calibrate the system with all brightness control knobs set to 00 and to 80. Measure the change at the control panel meters and at each remote station (TB 1-10) during the following temperature cycle:

Ambient Temp.	1 hour
-10°C	1 hour
Ambient Temp.	1 hour
$+55^{\circ}$C, 95% humidity	1 hour

14. Temperature Test - Remote Station

Repeat the test above with the equipment of one Remote Station in the controlled temperature chamber instead of the master station equipment.

15. Weather Proof Test - Remote Station

With one Remote Station equipment housed in its case, simulate conditions of heavy rain and wind for 1 hour. Repeat the test of paragraph 8 to verify correct operation.

WIRELESS CONTROL SYSTEM

FOR AIRPORT LIGHTING

CONTRACT FA-WA-4632

FINAL TEST DATA

Test Procedure Reference Par's 1, 2, 3, 11

	MASTER Ser. #1	REMOTE Ser. #2	REMOTE Ser. #3	REMOTE Ser. #4
R-F Frequency, mc	162.225	162.225	162.225	162.225
R-F Peak Power, watts	10	10	10	10
Peak FM Deviation, kc	± 1.0	± 1.0	±1.0	±1.0
Peak-to-Peak Discriminator Output for Given Deviation, Volts	3.5	3.5	3.5	3.3
Carrier Detector Sensitivity µv	5	5	5	5
Primary Voltage, volts	115	115	115	115
Primary Current, amps.				
STBY	1.4	1.1	1.1	1.1
OPER	1.6	1.2	1.2	1.2
HEAT	---	1.8	1.8	1.8
Primary Power, watts	180 max.	200 max.	200 max,	200 max.
Locking Provisions	---	OK	OK	OK
General Workmanship	OK	OK	OK	OK

DATE 6 November 1964

PERFORMED A. H. Ballard

WITNESSED BY B R Boynd

WIRELESS CONTROL SYSTEM

FOR AIRPORT LIGHTING

CONTRACT FA-WA-4632

FINAL TEST DATA

Test Procedure Reference Par's 4, 5, 6, 7

	CHAN. 1 (Remote #2)	CHAN. 2 (Remote #3)	CHAN. 3 (Remote #4
Panel Illumination			
FULL ON	OK	OK	OK
FULL OFF	OK	OK	OK
Response Time, Command	Immediate	Immediate	Immediate
Reply	1 sec.	1 sec.	1 sec.
Holding Time, Master Station	15 sec.	10 sec.	20 sec.
Remote Station	27 sec.	37 sec.	80 sec.
Brightness Command	00	00	00
Error Alarm (High)	20	20	20
Error Alarm (Low)	--	--	--
Brightness Command	20	20	20
Error Alarm (High)	40	40	40
Error Alarm (Low)	00	00	00
Brightness Command	40	40	40
Error Alarm (High)	60	60	60
Error Alarm (Low)	20	20	20
Brightness Command	60	60	60
Error Alarm (High)	80	80	80
Error Alarm (Low)	40	40	40
Brightness Command	80	80	80
Error Alarm (High)	100	100	100
Error Alarm (Low)	60	60	60
Brightness Command	100	100	100
Error Alarm (High)	--	--	--
Error Alarm (Low)	80	80	80

DATE 10 November 1964

PERFORMED BY

WITNESSED BY

WIRELESS CONTROL SYSTEM

FOR AIRPORT LIGHTING

CONTRACT FA-WA-4632

FINAL TEST DATA

Test Procedure Reference, Par. 8

Attenuation Between Stations 60 db

Environmental Conditions

Master Station Ser. #1	Ambient
Remote Station Ser. #2	Ambient
Remote Station Ser. #3	Ambient
Remote Station Ser. #4	Ambient

	CHAN. 1 (Remote #2)	CHAN. 2 (Remote #3)	CHAN. 3 (Remote #4)
Carrier Selector Position	1	2	3
Reply Selector Position	INT.	INT.	INT.
Brightness Command	00	00	00
Remote Output	00	01	00
Reply	00	00	00
Brightness Command	20	20	20
Remote Output	22	22	21
Reply	22	21	21
Brightness Command	40	40	40
Remote Output	42	42	41
Reply	42	42	41
Brightness Command	60	60	60
Remote Output	61	61	60
Reply	61	61	59
Brightness Command	80	80	80
Remote Output	80	80	80
Reply	80	80	80
Brightness Command	100	100	100
Remote Output	101	101	102
Reply	100	100	100

DATE 9 November 1964

PERFORMED BY A. H. Ballard

WITNESSED BY [illegible]

Test Procedure Reference Par. 9

WIRELESS CONTROL SYSTEM FOR
AIRPORT LIGHTING FINAL TEST DATA

DISTURBED CARRIER (NOMINAL 80%)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	x	-005	-005	030	-010	-010	-015	000	-010	-005	005	010	-020	000	010	005
2	005	x	000	020	000	010	-010	-005	000	-020	005	-005	-010	030	000	005
3	000	000	x	-005	-005	-005	-010	010	005	005	-040	-030	005	010	000	020
4	-020	005	010	x	-010	-010	-020	000	000	005	-020	-010	000	010	000	020
5	-020	000	010	020	x	-005	-010	005	-030	-030	005	005	020	000	005	010
6	010	000	-010	-020	010	x	-005	000	-010	010	+005	010	000	020	000	010
7	-020	-020	-015	-015	-020	000	x	000	000	005	005	005	000	000	005	010
8	000	-005	000	000	-005	000	005	x	000	000	005	005	000	005	000	010
9	-010	-010	000	010	-015	030	020	000	x	010	010	010	-010	010	010	000
10	000	-020	000	-010	010	020	020	000	000	x	005	010	-010	020	-005	010
11	000	000	030	-030	000	010	020	000	010	020	x	-020	010	000	010	020
12	-005	-010	020	030	-005	000	-010	010	005	005	020	x	005	-005	010	005
13	-010	005	010	000	010	-010	-005	-010	-020	020	010	015	x	-010	010	010
14	010	010	000	-005	000	010	005	-010	020	020	-010	010	015	x	010	005
15	000	000	010	010	005	000	000	010	000	010	010	010	005	020	x	-030
16	000	-005	005	-005	000	000	005	000	005	000	-010	030	005	010	030	x

DISTURBING CARRIER
(0-100%)

ALL ENTRIES TIMES 0.1%

DATE 6 November 1964
PERFORMED BY C. H. Ballard
WITNESSED BY B. E. Bryant

WIRELESS CONTROL SYSTEM

FOR AIRPORT LIGHTING

CONTRACT FA-WA-4632

FINAL TEST DATA

Test Procedure Reference, Par. 10

Attenuation Between Stations (A) 60 db (B) 120 db

Environmental Conditions

Master Station Ser. #1	Ambient
Remote Station Ser. #2	Ambient
Remote Station Ser. #3	Ambient
Remote Station Ser. #4	Ambient

	CHAN. 1 (Remote #2)	CHAN. 2 (Remote #3)	CHAN. 3 (Remote #4)	
Carrier Selector Position	1	2	3	
Reply Selector Position	INT.	INT.	INT.	
Brightness Command	00/80	00/80	00/80	
Remote Output	00/80	00/80	00/80	(A)
Reply	00/80	00/80	00/80	
Brightness Command	00/80	00/80	00/80	
Remote Output	00/80	00/80	00/80	(B)
Reply	00/80	00/80	00/80	

NOTE: Correct operation was also verified in an on-the-air test between master station and remote station #4. Range was approximately 1.25 miles, line-of-sight.

DATE 9 November 1964

PERFORMED BY A. H. Ballard

WITNESSED BY [illegible]

WIRELESS CONTROL SYSTEM

FOR AIRPORT LIGHTING

CONTRACT FA-WA-4632

FINAL TEST DATA

Test Procedure Reference, Par. 13

Attenuation Between Stations 60 db

Environmental Conditions

(A) Ambient
(B) $-10^{\circ}C$
(C) $+55^{\circ}C$, 95% Hum.

Master Station Ser. #1 ______

Remote Station Ser. #2 Ambient

Remote Station Ser. #3 Ambient

Remote Station Ser. #4 Ambient

	CHAN. 1 (Remote #2)	CHAN. 2 (Remote #3)	CHAN. 3 (Remote #4)	
Carrier Selector Position	1	2	3	
Reply Selector Position	INT.	INT.	INT.	
Brightness Command	00/80	00/80	00/80	
Remote Output	00/80	00/80	00/80	(A)
Reply	00/80	00/80	00/80	
Brightness Command	00/80	00/80	00/80	
Remote Output	01/80	00/78	00/76	(B)
Reply	02/78	04/79	00/75	
Brightness Command	00/80	00/80	00/80	
Remote Output	08/80	00/80	00/80	(A)
Reply	00/80	00/90	00/80	
Brightness Command	00/80	00/80	00/80	
Remote Output	00/79	00/80	00/80	(C)
Reply	-02/76	-02/78	-01/80	

DATE 3 November 1964

PERFORMED BY A. H. Ballard

WITNESSED BY [illegible]

WIRELESS CONTROL SYSTEM

FOR AIRPORT LIGHTING

CONTRACT FA-WA-4632

FINAL TEST DATA

Test Procedure Reference, Par. 14, 15

Attenuation Between Stations 60 db

Environmental Conditions

Master Station Ser. #1 Ambient

Remote Station Ser. #2 Ambient

Remote Station Ser. #3 Ambient

Remote Station Ser. #4 ____________

(A) Simulated rain, Wind
(B) Ambient
(C) $-10^{\circ}C$
(D) $+55^{\circ}C$, 95% Hum.

	CHAN. 1 (Remote #2)	CHAN. 2 (Remote #3)	CHAN. 3 (Remote #4)	
Carrier Selector Position	1	2	3	
Reply Selector Position	INT.	INT.	INT.	
Brightness Command			NON. OP	
Remote Output	NON. OP.	NON. OP	(NO VISIBLE	(A)
Reply			LEAKAGE)	
Brightness Command	00/80	00/80	00/80	
Remote Output	00/80	00/80	00/80	(B)
Reply	00/80	00/80	00/80	
Brightness Command	00/80	00/80	00/80	
Remote Output	00/80	00/80	05/80	(C)
Reply	00/80	00/80	06/75	
Brightness Command	00/80	00/80	00/80	
Remote Output	00/80	00/80	00/80	(B)
Reply	00/80	00/80	00/80	
Brightness Command	00/80	00/80	00/80	
Remote Output	00/80	00/80	-01/77	(D)
Reply	00/80	00/80	-04/78	

DATE 4 November 1964

PERFORMED BY A.H. Balboni

WITNESSED BY [illegible signature]

Bernard Electronics Company, Wash., D. C.
WIRELESS CONTROL SYSTEM FOR AIRPORT LIGHTING, By A. H. Ballard,
Final Report, Dec. 1964, 69 pp., incl. 22 illus.
(Contract No. FA-WA-4632, Project No. 221-140-02C (423-1)
Report No. RD-65-8).

Unclassified Report

An experimental system for wireless control and monitoring of airport lighting was developed with the objective of providing a cheaper more flexible and reliable system than existing cable systems.

The system provides 16 channel capacity on a single FM carrier with a maximum range of 3 miles. Three channels (selectable) provide on-off, 5-step or continuous control in the form of 0-10 volt d-c commands. Remote stations reply automatically with identical signals to actuate displays at the master station. Electrical comparison of signals indicate incorrect reply or failure in any channel. Failsafe provisions at each remote station switch the lighting equipment to full on, full off, or the last commanded brightness in the event of system failure.

High spectrum efficiency, and maximum rejection of noise, crosstalk, and interference is achieved through the use of ORTHOMUX, a previously developed multiplex technique. Orthogonal pulse waveforms are employed as subcarrier signals, which are generated digitally and amplitude-modulated by diode multipliers. Channel separation and demodulation is accomplished by correlation with locally-generated subcarrier waveforms. All remote stations are automatically synchronized to a timing reference subcarrier by similar correlation techniques.

When engineered for quantity production, system cost is estimated to be approximately $2,000 per 2-way channel, including r-f equipment.

UNCLASSIFIED

I. Ballard, Arthur H.
II. Contract No. FA-WA-4632
III. Project No. 221-140-02C (423-1)
IV. Report No. RD-65-8

DESCRIPTORS

Radio Communication System
Multiplex
Command and Control
Waveform Modulation
Telemetering
Lighting Equipment
Design

UNCLASSIFIED

Bernard Electronics Company, Wash., D. C.
WIRELESS CONTROL SYSTEM FOR AIRPORT LIGHTING, By A. H. Ballard,
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High spectrum efficiency, and maximum rejection of noise, crosstalk, and interference is achieved through the use of ORTHOMUX, a previously developed multiplex technique. Orthogonal pulse waveforms are employed as subcarrier signals, which are generated digitally and amplitude-modulated by diode multipliers. Channel separation and demodulation is accomplished by correlation with locally-generated subcarrier waveforms. All remote stations are automatically synchronized to a timing reference subcarrier by similar correlation techniques.

When engineered for quantity production, system cost is estimated to be approximately $2,000 per 2-way channel, including r-f equipment.

UNCLASSIFIED

I. Ballard, Arthur H.
II. Contract No. FA-WA-4632
III. Project No. 221-140-02C (423-1)
IV. Report No. RD-65-8

DESCRIPTORS

Radio Communication System
Multiplex
Command and Control
Waveform Modulation
Telemetering
Lighting Equipment
Design

UNCLASSIFIED

Bernard Electronics Company, Wash., D. C.
WIRELESS CONTROL SYSTEM FOR AIRPORT LIGHTING, By A. H. Ballard,
Final Report, Dec. 1964, 69 pp., incl. 22 illus.
(Contract No. FA-WA-4632, Project No. 221-140-02C(423-1)
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